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Probing oscillations into sterile neutrinos with astrophysics, cosmology and experiments…

"Sterile Neutrinos in all sauces"

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Introduction and Purpose

We want to study **Sterile Neutrinos**

i.e. - (light) spin 1/2 fermions,
- neutral under all SM forces,
- have a mixing with active ν.

Oscillations into $\boldsymbol{\nu_s}$ are now **excluded** as the **dominant** solution in solar and atmospheric neutrinos:

solar: ~~$\nu_e \rightarrow \nu_s$~~ ? no, $\nu_e \rightarrow \nu_{\mu,\tau}$ (SNO) (details…)

atmo: ~~$\nu_\mu \rightarrow \nu_s$~~ ? no, $\nu_\mu \rightarrow \nu_\tau$ (SK, Macro) (details…)

Now the **relevant issues** become:

- which **subdominant** role is still possible for ν_s ?
- where can we **detect** the ν_s ?
- how can we **detect** the ν_s ?

Perform a complete analysis:

(1) for any possible $\nu_{e,\mu,\tau}$ - ν_s mixing pattern

(2) including the established ν_e-$\nu_{\mu,\tau}$ and ν_μ-ν_τ mixing (= in a full 4ν mixing formalism)

(3) study *all* neutrino sources (experiments, astrophysics, cosmology)

- look for sterile **evidence** in present data. None.
- set present **bounds**
- identify future **signals**

Are sterile neutrinos still interesting at all?

- Yes, "light neutral fermions" in so many Beyond the SM constructions…

  -behave effectively as ν_s
  -parameterize with θ_s , Δm_s^2

- Yes, sterile neutrinos invoked for so many "puzzles" … (

?)

- **…LSND**

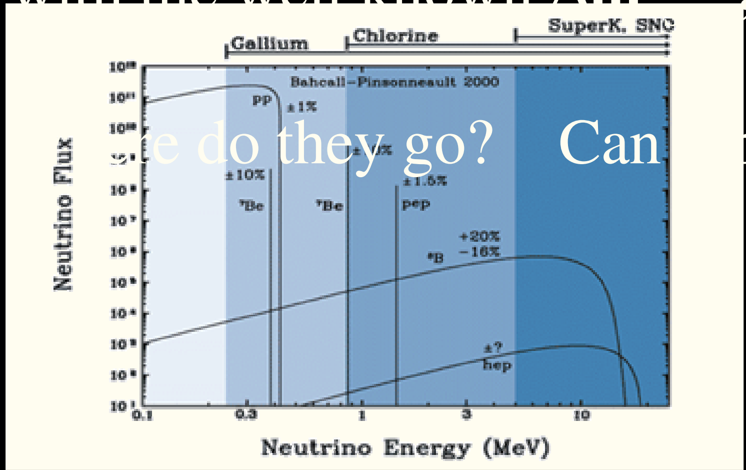
right-handed neutrino
axino
goldstino
majorino
branino
dilatino
radino
familino
modulino
mirror fermions
…

pulsar kicks
r-process nucleosynthesis
Dark Matter
galactic ionization
…

Pure $\nu_e \to \nu_s$ solution for solar neutrinos

Evidence for oscillations is disappearance of solar ν_e, with the well known Δm^2 , θ_{sun} .

SNO has detected the $\nu_{\mu,\tau}$ component of solar flux .



Bahcall webpage

... do they go? Can ... be $\nu_e \to \nu_s$?

SNO:

CC	$\nu_e + d \to p + p + e^-$
NC	$\nu_x + d \to p + n + \nu_x$
ES	$\nu_x + e^- \to \nu_x + e^-$

SNO CC (2001) :

$\Phi_{ES}^{SK} > \Phi_{CC}^{SNO}$ ⇨ $\phi(\nu_{\mu\tau}) = 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2}\text{ s}^{-1}$ ➡ ν_e- ν_s out 3.2 σ

SNO NC (2002) : $\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat})^{+0.48}_{-0.45}(\text{syst})$ ➡ ν_e- ν_s excluded 5.3 σ

(~3σ with no undistorted ^{8}B spectrum)

SNO salt NC (2003) : … ➡ > 7σ

Instead: $\nu_e \to \nu_{\mu,\tau}$ $\Delta m^2_{\text{sun}} \simeq 7.1\ 10^{-5}\text{ eV}^2$ $\theta_{\text{sun}} \simeq 32^o$ (LMA MSW)

(+KamLAND)

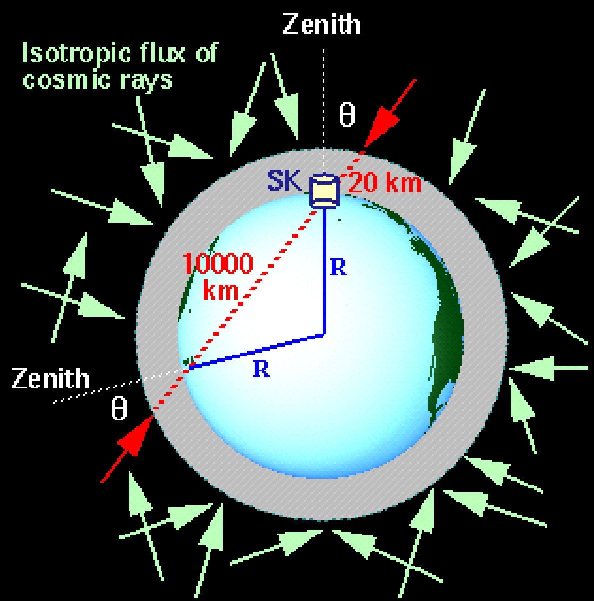
go to "Sterile effect in sun"

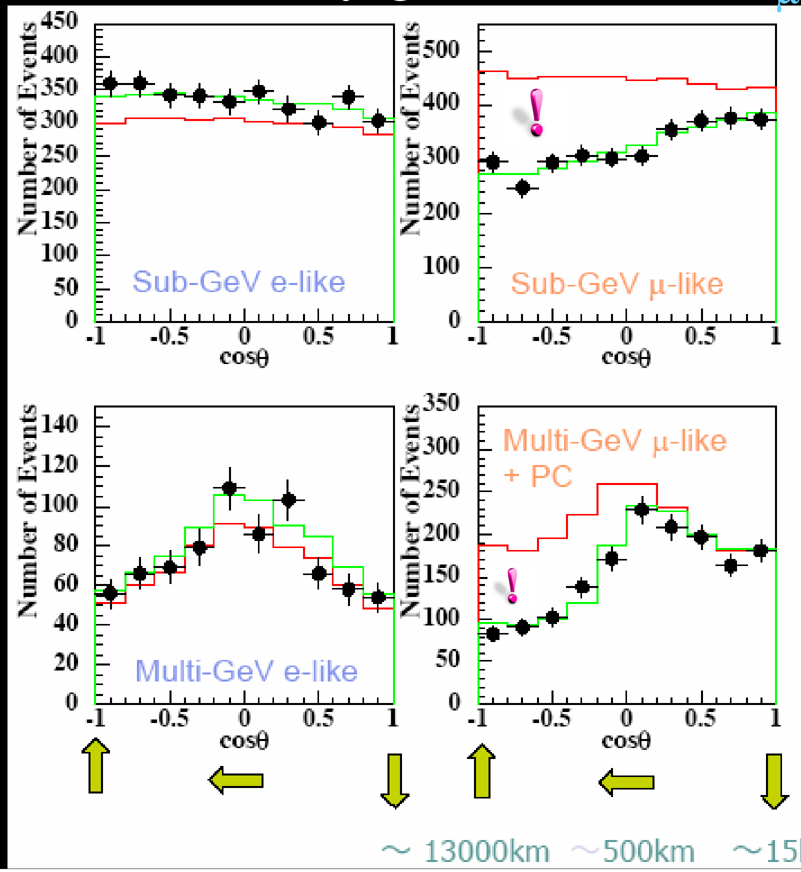
Pure $\nu_\mu \rightarrow \nu_s$ solution for atmospheric neutrinos

: matter effects and NC favor ν_τ vs to ν_s .

Evidence for oscillations is disappearance of ν_μ "from below", with the well known Δm^2_{atm} , θ_{atm} . Where do they go? Can it be $\nu_\mu \rightarrow \nu_s$?

Basics:





SK coll.

If $\nu_\mu \rightarrow \nu_s$:

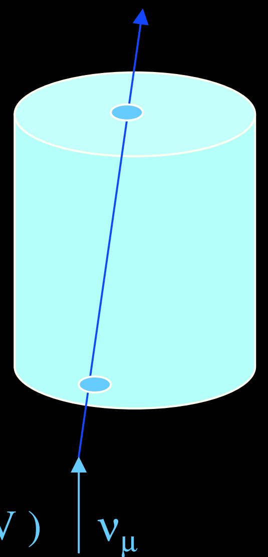
(1) matter effects crossing the Earth reduce oscillations

($V_\mu = V_\tau \neq V_s = 0$)

⇩

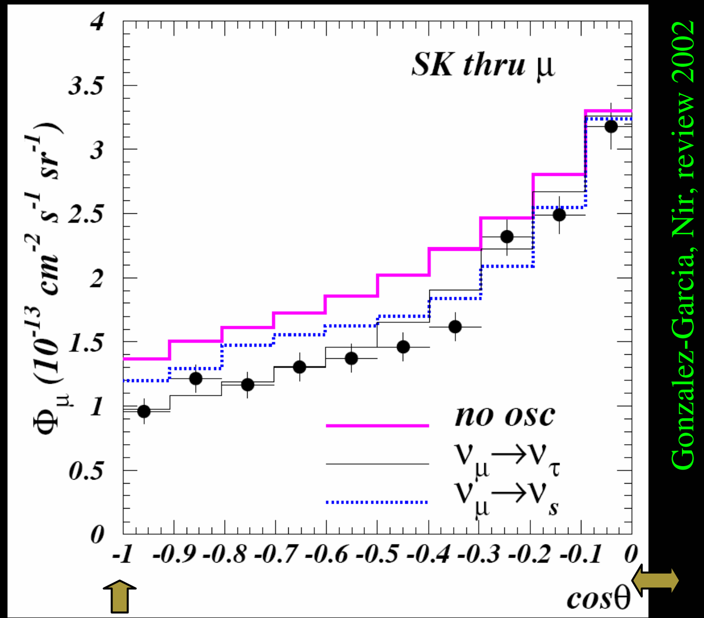
larger flux of thru-μ

($\mu^\pm$ produced in the rock below the detector by upgoing high-energy ν_μ)



(E_ν ~ 100 GeV) ν_μ

…but:



SK, Macro data

favor $\nu_\mu \rightarrow \nu_\tau$

$\nu_\mu \rightarrow \nu_s$ disfavored $\geq 3\sigma$

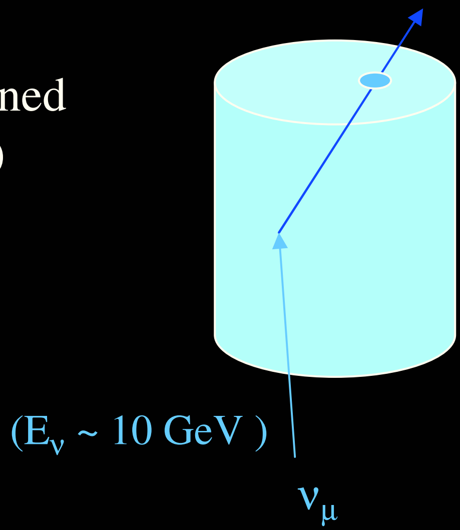
If $\nu_\mu \longrightarrow \nu_s$:

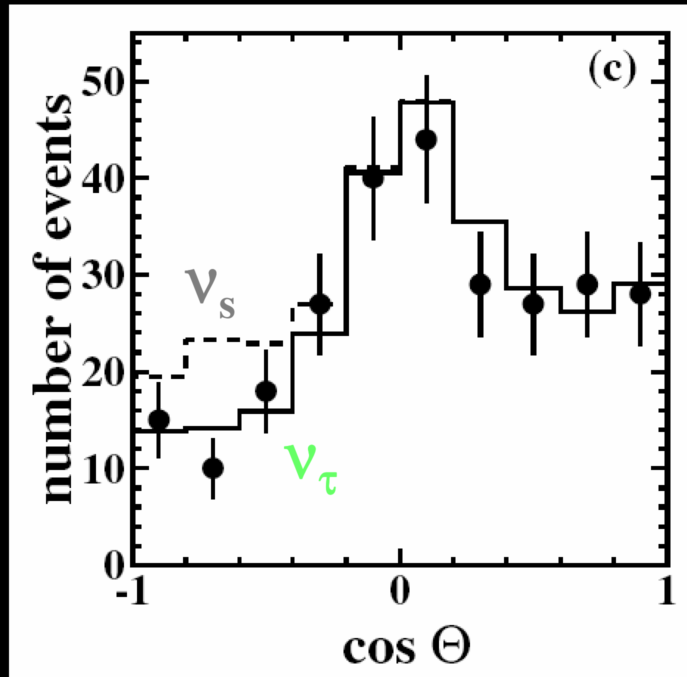
(1b) matter effects crossing the Earth reduce oscillations

⇩

larger number of PC events

(Partially Contained events by ν_μ)





SK coll. PRL85, 2000

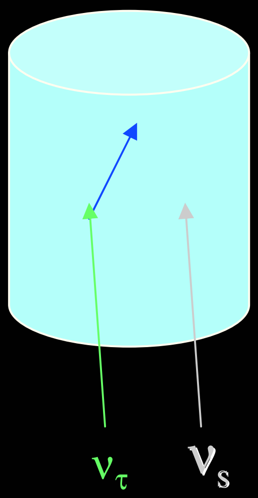
…but: SK

favor $\nu_\mu \longrightarrow \nu_\tau$

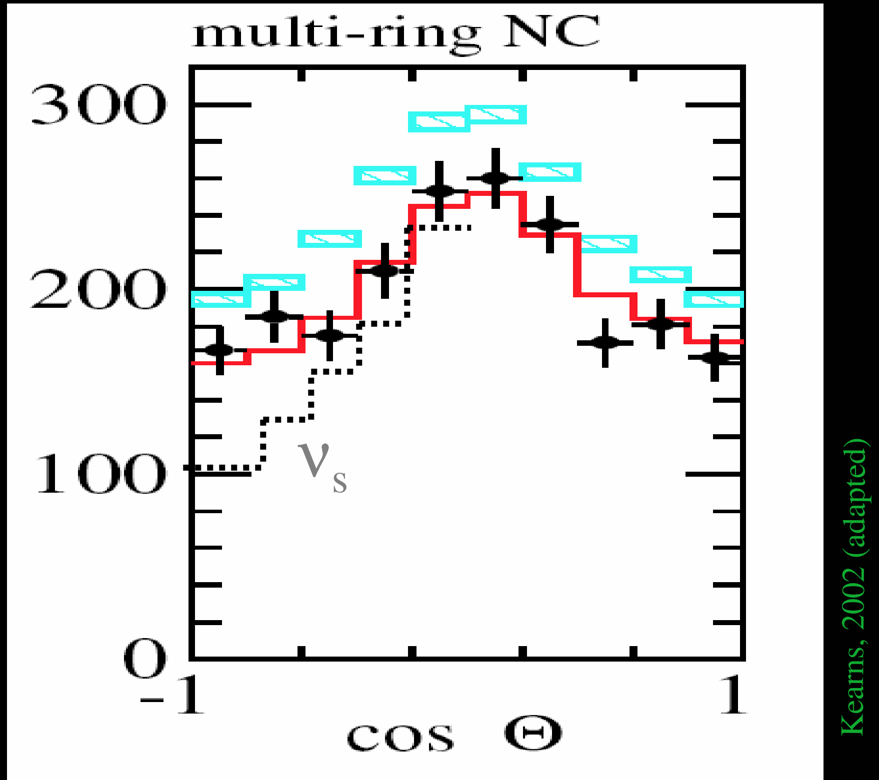
$\nu_\mu \longrightarrow \nu_s$ disfavored $\geq 2\sigma$

If $\nu_\mu \rightarrow \nu_s$:

(2) less NC events upward



…but:

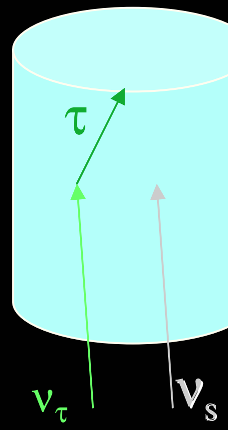


SK favor $\nu_\mu \rightarrow \nu_\tau$

$\nu_\mu \rightarrow \nu_s$ disfavored ~ 2σ

If $\nu_\mu \rightarrow \nu_s$:

(3) τ appearance from below



but: small statistics…

⇓

not used

Global Analysis excludes $\nu_\mu \rightarrow \nu_s$ at $\sim 7\,\sigma$

Instead: $\nu_\mu \rightarrow \nu_\tau$

(+Macro +Soudan2 +K2K)

$$\Delta m^2_{\rm atm} \simeq 2.6\ 10^{-3}\,{\rm eV}^2 \qquad \theta_{\rm atm} \simeq 45^o$$

go to "Sterile effects in atmo neutrinos"

4ν mixing formalism

Present bounds are computed in a limited 2ν formalism: $\nu_l \longrightarrow \cos\theta_s\, \nu_l' + \sin\,\theta_s\, \nu_s$.

We want instead a full 4ν formalism.

A simple parametrization:

more details

define a **complex unit 3-versor** $\vec{n}$

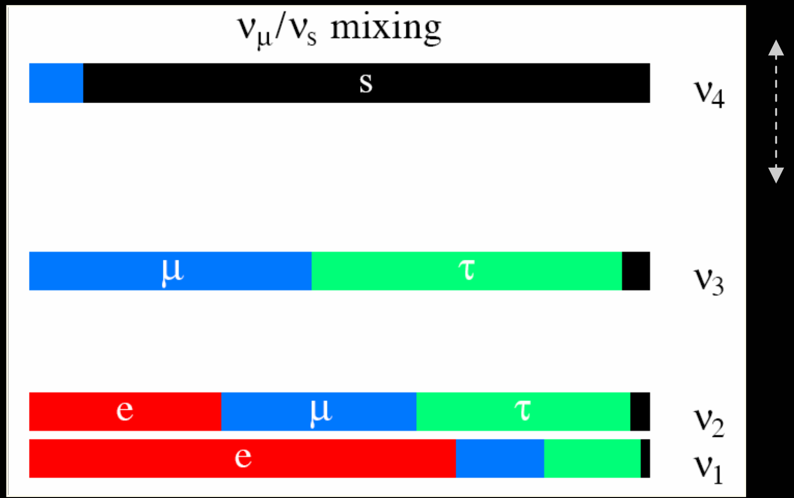
$\vec{n}$ identifies an arbitrary combination of active ν :

$$\vec{n}\cdot\vec{\nu} = n_e\nu_e + n_\mu\nu_\mu + n_\tau\nu_\tau = n_1\nu_1 + n_2\nu_2 + n_3\nu_3$$

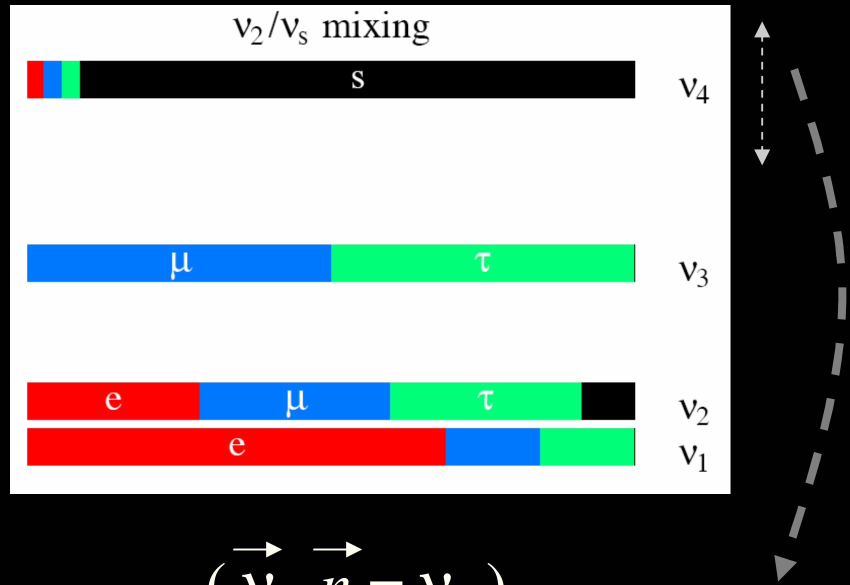
which mixes with $\boldsymbol{\nu_s}$ with a single angle θ_S

In the following:

ν_s has arbitrary mass m_4 and it mixes with angle θ_s
with ν_e OR ν_μ OR ν_τ OR ν_1 OR ν_2 OR ν_3



$(\vec{\nu}_l \cdot \vec{n} = \nu_\mu)$



$(\vec{\nu}_i \cdot \vec{n} = \nu_2)$

Also: take best-fit values for θ_{sun} and θ_{atm},
choose $\theta_{13} = 0$, Normal Hierarchy.

Full 4ν mixing formalism

Present bounds are computed in a limited 2ν formalism: $\nu_l \longrightarrow \cos\theta_s\, \nu_l' + \sin\theta_s\, \nu_s$.

We want a full 4ν formalism.

3 neutrinos: $\nu_e\, \nu_\mu\, \nu_\tau \longleftrightarrow \nu_1\, \nu_2\, \nu_3$

$$\nu_\ell = U_{\ell i} \nu_i$$

3 angles $\theta_{12}\, \theta_{23}\, \theta_{13}$

(and 1 phase δ)

$$U_{li} = U_{23}\, U_{13}\, U_{12}$$

(3x3 rotations in *ij*)

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$

4 neutrinos: $\nu_e\ \nu_\mu\ \nu_\tau\ \nu_s \longleftrightarrow \nu_1\ \nu_2\ \nu_3\ \nu_4$

$$\nu_{e,\mu,\tau,s} = V \cdot \nu_{1,2,3,4}$$

add 3 angles θ_{14} θ_{24} θ_{34} $\quad R_{14}$, R_{24} , R_{34}

(and add 2 phases)

(4x4 rotations in *ij*)

- ν_s mixes with the *flavor* eigenstates

$$V = R_{34} R_{24} R_{14}\, U_{\ell i}$$

(e.g. θ_{14} mixes ν_e / ν_s , θ_{24} mixes ν_μ / ν_s …)

$$\nu_\ell = U_{\ell i} \nu_i$$

- ν_s mixes with the *matter* eigenstates

$$V = U_{\ell i} R_{34} R_{24} R_{14}$$

(e.g. θ_{14} mixes ν_1 / ν_s , θ_{24} mixes ν_2 / ν_s …)

A simple parametrization:

define a **complex unit 3-versor** $\vec{n}$ ($\longleftrightarrow$ 3 angles + 2 phases)

$\vec{n}$ identifies an arbitrary combination of active ν :

$$\vec{n} \cdot \vec{\nu} = n_e \nu_e + n_\mu \nu_\mu + n_\tau \nu_\tau = n_1 \nu_1 + n_2 \nu_2 + n_3 \nu_3$$

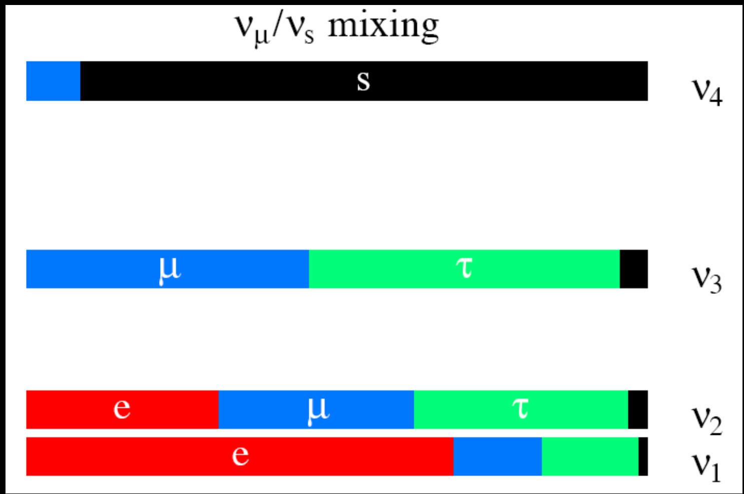
which mixes with ν_s with a single angle θ_s

Explicitly:

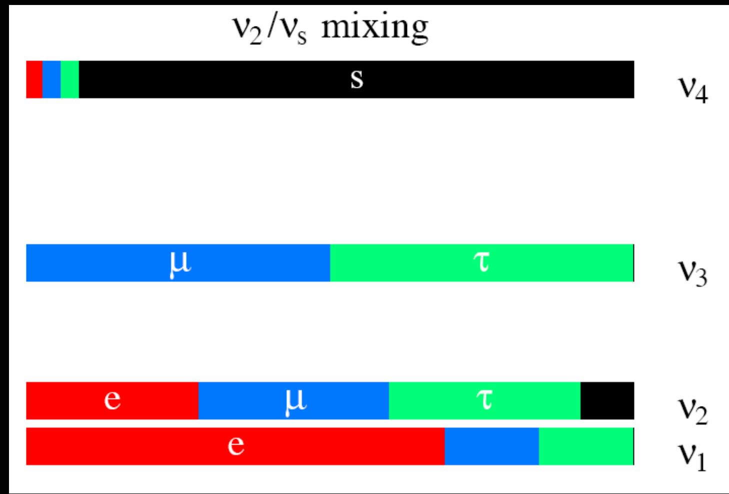
$$V = \begin{matrix} \\ \nu_\ell \\ \nu_\mathrm{s} \end{matrix} \begin{matrix} \nu_i & \nu_4 \\ \left(\begin{matrix} U_{\ell i} - n_i n_\ell^* (1 - \cos\theta_\mathrm{s}) \\ -n_i \sin\theta_\mathrm{s} \end{matrix} \right. & \left. \begin{matrix} n_\ell^* \sin\theta_\mathrm{s} \\ \cos\theta_\mathrm{s} \end{matrix} \right) \end{matrix}$$

In the following:

ν_s has arbitrary mass $\boldsymbol{m_4}$ and it mixes with angle $\boldsymbol{\theta_s}$
with ν_e OR ν_μ OR ν_τ OR ν_1 OR ν_2 OR ν_3

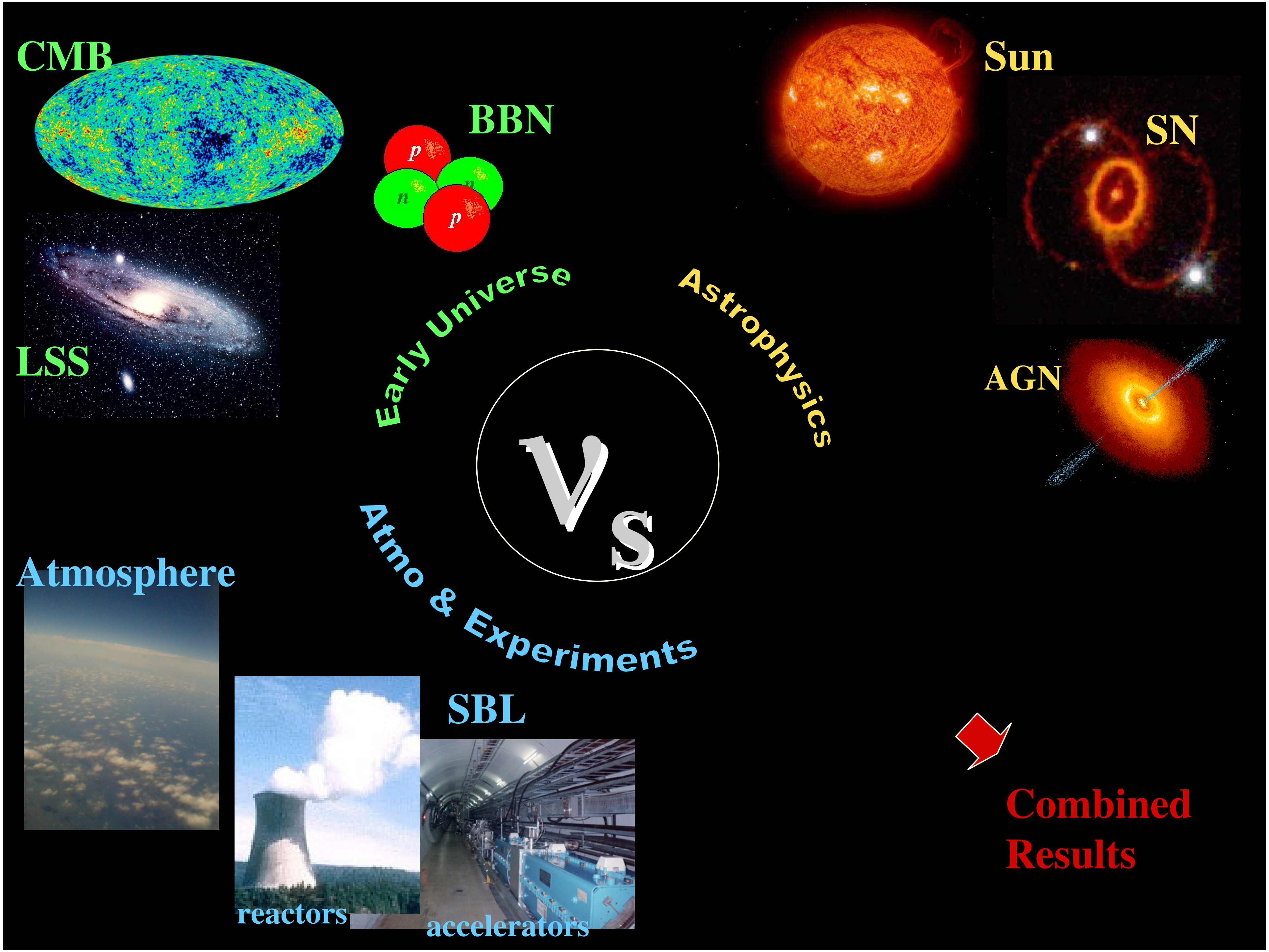


$$(\vec{\nu}_l \cdot \vec{n} = \nu_\mu)$$



$$(\vec{\nu}_i \cdot \vec{n} = \nu_2)$$

Also: take best-fit values for θ_{sun} and θ_{atm} ,
choose $\theta_{13} = 0$, Normal Hierarchy.



CMB
BBN
LSS
Early Universe
Sun
SN
AGN
Astrophysics
ν_s
Atmosphere
Atmo & Experiments
SBL
reactors
accelerators
Combined Results

Sterile effects in the Early Universe

Neutrinos in the Early Universe are:

(1) a lot (as abundant as photons)

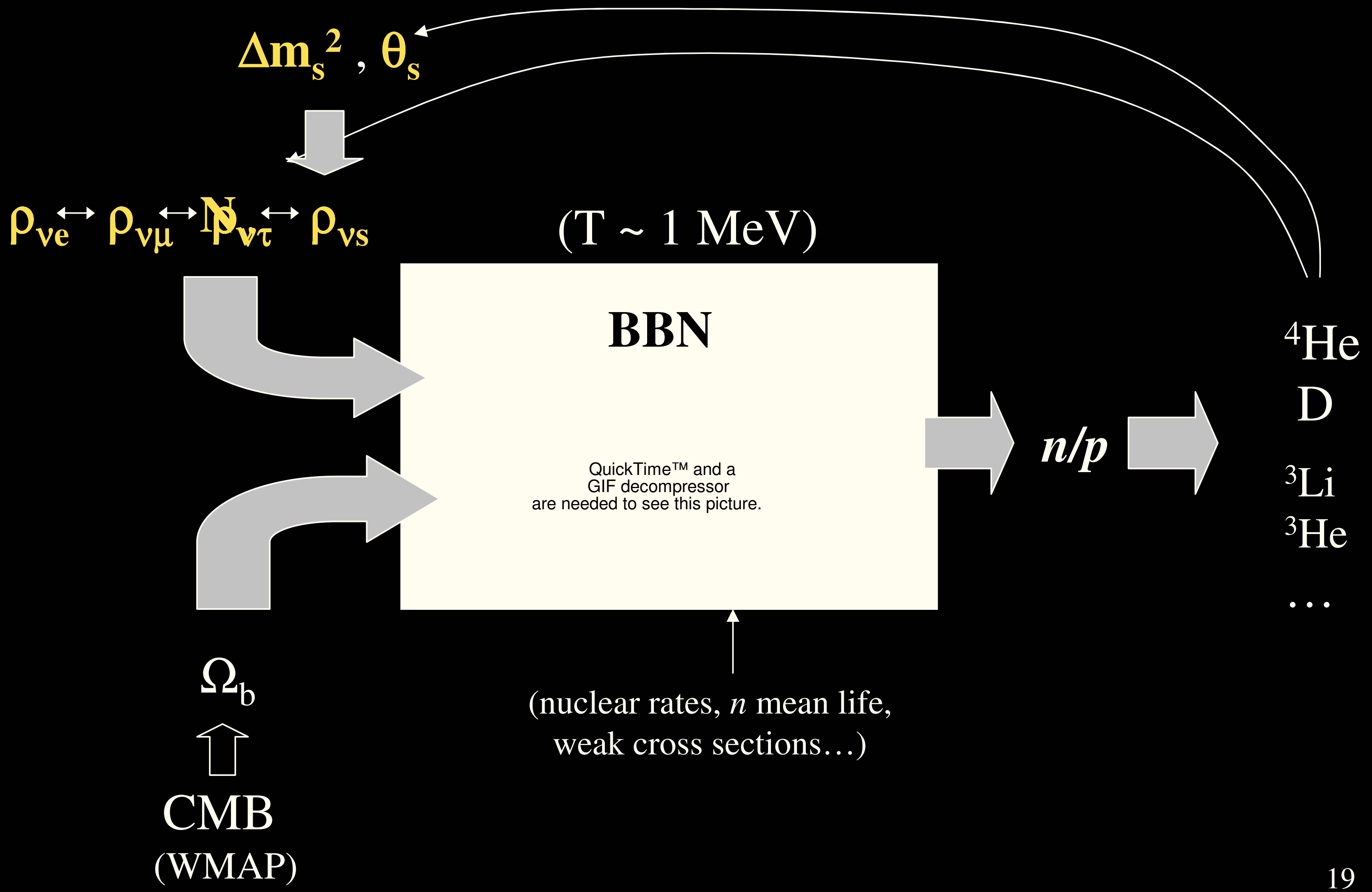
(2) the main component of the (relativistic) energy density that sets the expansion rate

(3) trapped in the dense early plasma ⇨ non trivial matter effects

(4) important for the outcoming chemical composition

An extra ν_s can make a big difference.

BigBang Nucleosynthesis



Roadmap (= What we do)

For every choice of Δm_s^2 , θ_s ,
for T >> MeV ⟶ 0.07 MeV follow:
(BBN ends, les jeux sont fait)

1 kinetic equ.s for neutrino densities $\rho_{\nu e}(T)$, $\rho_{\nu\mu}(T)$, $\rho_{\nu\tau}(T)$, $\rho_{\nu s}(T)$

2 equation for ***n/p***

3 equations of light nuclei (^{4}He , D) production

4 (^{4}He , D) observations

Assumptions:
- no large lepton asymmetries
- neglect spectral distortions

Where does a ν_s enter the BBN game?

(A) ν_s production ⇒ larger total energy density ⇒ faster expansion
(B) mixing ν_e - ν_s ⇒ depletion of ν_e ⇒ effect on $n \leftrightarrow p$ reactions

1 Neutrino kinetic equations

4x4 neutrino density matrix ρ

scatterings and absorptions

$$\frac{d\rho}{dt} \equiv \frac{dT}{dt}\frac{d\rho}{dT} = -i\,[\mathcal{H}_m, \rho] - \{\Gamma, (\rho - \rho^{\rm eq})\}$$

Dolgov, 1981
Barbieri, Dolgov 1990

diag(1,1,1,0)

$$\mathcal{H}_m = \frac{1}{2E_\nu}\left[V\,{\rm diag}(m_1^2, m_2^2, m_3^2, m_4^2)\,V^\dagger + E_\nu {\rm diag}(V_e, V_\mu, V_\tau, 0)\right]$$

$\dot{T} \sim -H(T,\rho)\,T$

Active/sterile mixing parameters

Hubble parameter contains $\underbrace{\rho_{\nu e}+\rho_{\nu\mu}+\rho_{\nu\tau}+\rho_{\nu s}}$

$H = (\,8\pi G_N/3\ \rho_{tot}\,)^{1/2}$

$$V_e = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\rm F}\frac{T}{M_W^2}\left(T^4 + \frac{1}{2}T_\nu^4 \cos\theta_W \rho_{ee}\right)$$

$$V_\mu = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\rm F}\frac{TT_\nu^4}{M_W^2}\left(\frac{1}{2}T_\nu^4 \cos\theta_W \rho_{\mu\mu}\right)$$

$$V_\tau = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\rm F}\frac{TT_\nu^4}{M_W^2}\left(\frac{1}{2}T_\nu^4 \cos\theta_W \rho_{\tau\tau}\right)$$

$$V_s = 0$$

ν thermal masses

What happens:

- for T >> MeV, matter effects suppress mixing $\rho_{\nu s} = 0$
- as T ↘ , at a certain point
  oscillations $\nu_{active} \longleftrightarrow \nu_s$ can begin $\rho_{\nu s} > 0$

  when & how depend on Δm_s^2, θ_s
- + redistribution $\nu_{active} \longleftrightarrow \nu_{active}$
- meanwhile: ν decouple at *T* ~ few MeV, e^+e^- annihilate
- Output: $\rho_{\nu e}(T)$, $\rho_{\nu\mu}(T)$, $\rho_{\nu\tau}(T)$, $\rho_{\nu s}(T)$

2 n/p ratio

$$\dot{r} \equiv \frac{dT}{dt}\frac{dr}{dT} = \Gamma_{p\to n}(1-r) - r\Gamma_{n\to p} \qquad r = \frac{n_n}{n_n + n_p}$$

$\dot{T} \sim -H(T,\rho)\,T$

Hubble parameter contains $\rho_{\nu e}+\rho_{\nu\mu}+\rho_{\nu\tau}+\rho_{\nu s}$

rates of weak interactions:

$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$

$$n + \nu_e \longleftrightarrow p + e^-$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}_e.$$

depend on $\rho_{\nu e}$, $\rho_{\overline{\nu e}}$

Bottom line: *where does a ν_s enter the game?*

(A) total energy density ⇒ expansion parameter

(B) depletion of ν_e density ⇒ weak rates

3 Light elements production

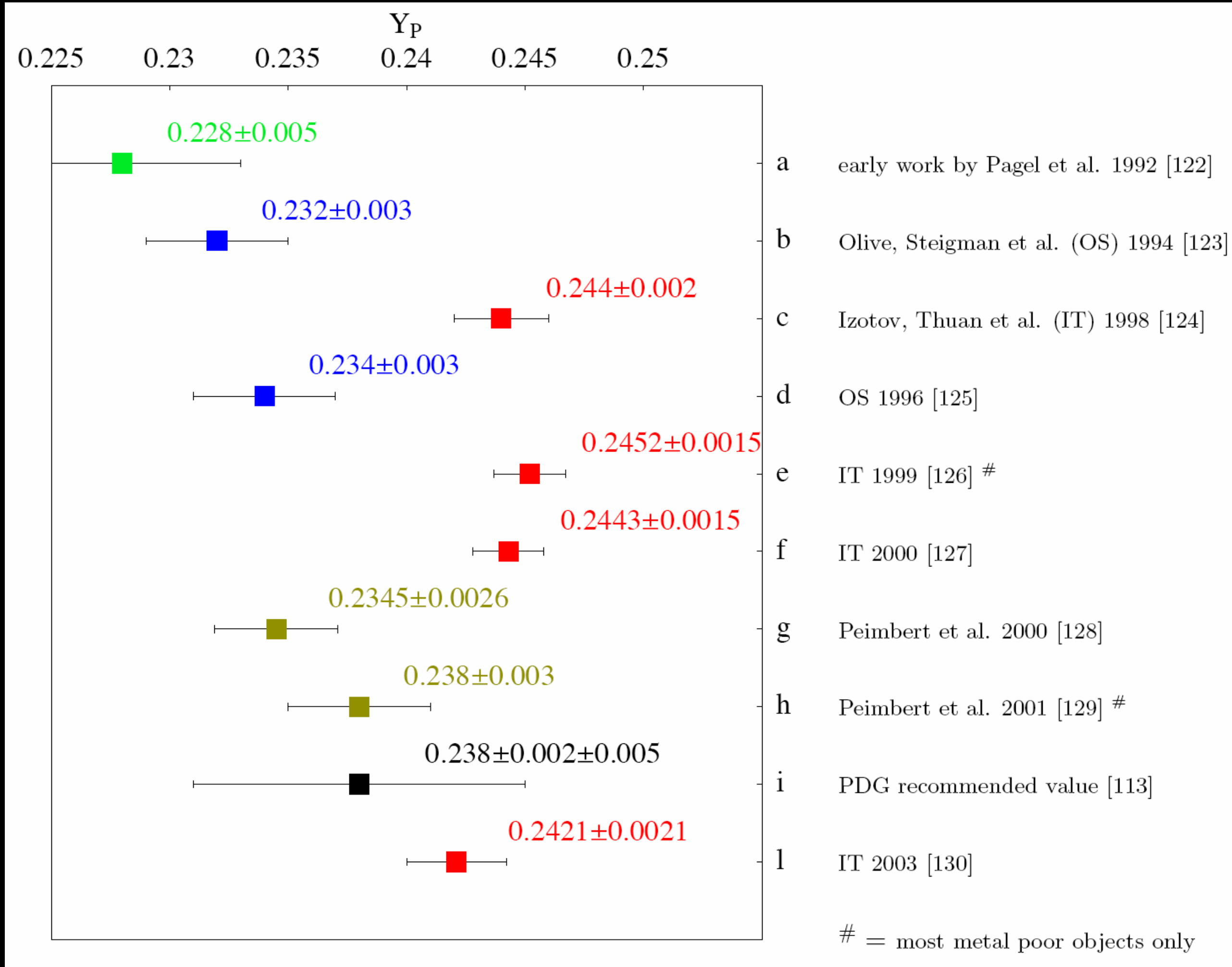
A network of Boltzman equations with up-to-date nuclear rates…

4 Observations

Determinations of primordial ^{4}He are controversial.

Very conservatively:

$Y_{^4He}$= (24 ±1)%

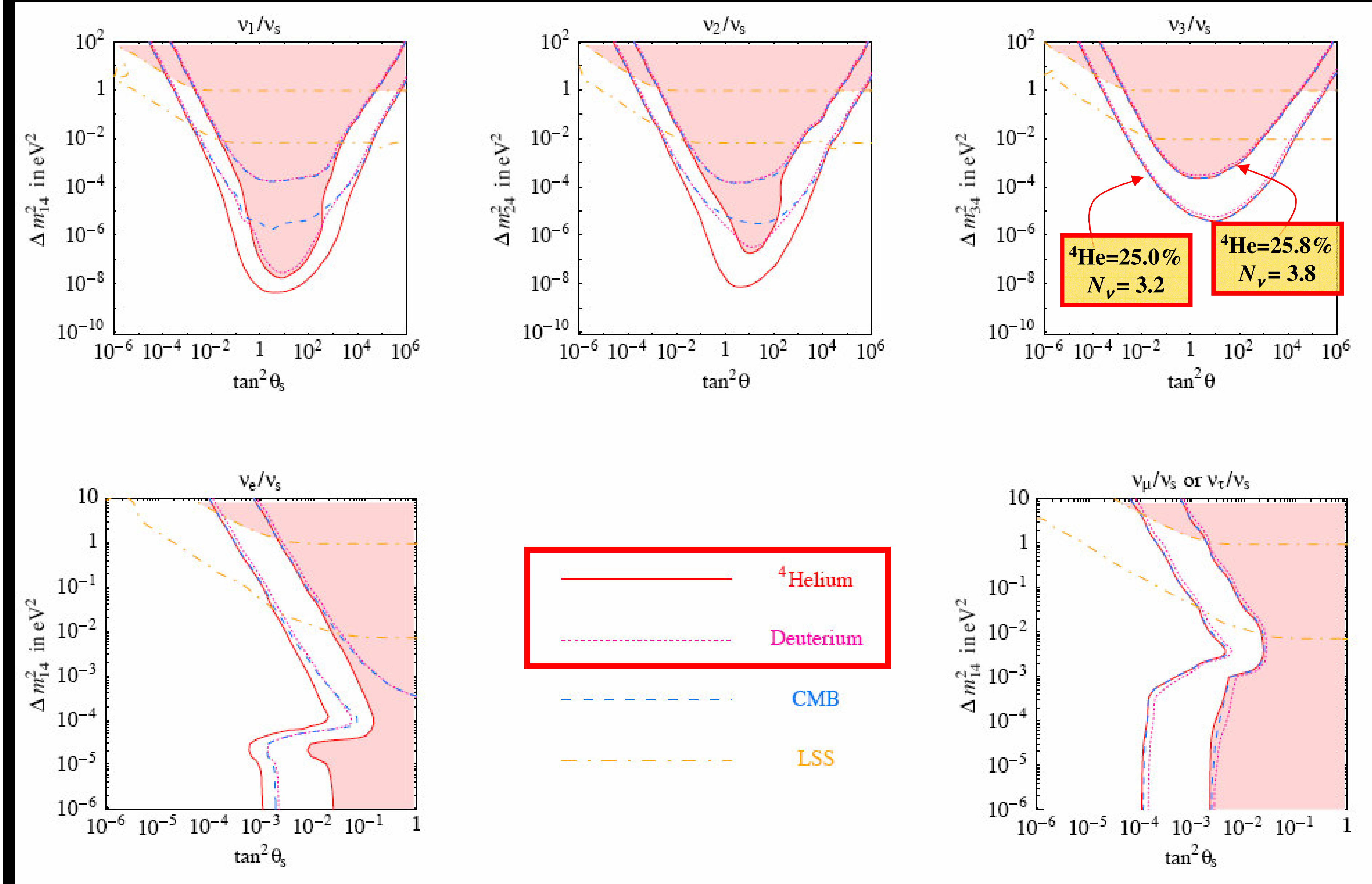


Determinations of primordial D are still imprecise.

Conservatively:

Y_D= (2.8 ±0.5) 10^{-5}

Bounds in the parameter space



Large Scale Structure

The primordial free streaming
of massive neutrinos
affects
the LSS power spectrum
observed today.

⇩

Upper bound on:

$$\Omega_\nu h^2 = \frac{\mathrm{Tr}[m \cdot \rho]}{93.5\,\mathrm{eV}}$$

$\nu_{1,2,3}$ and ν_s

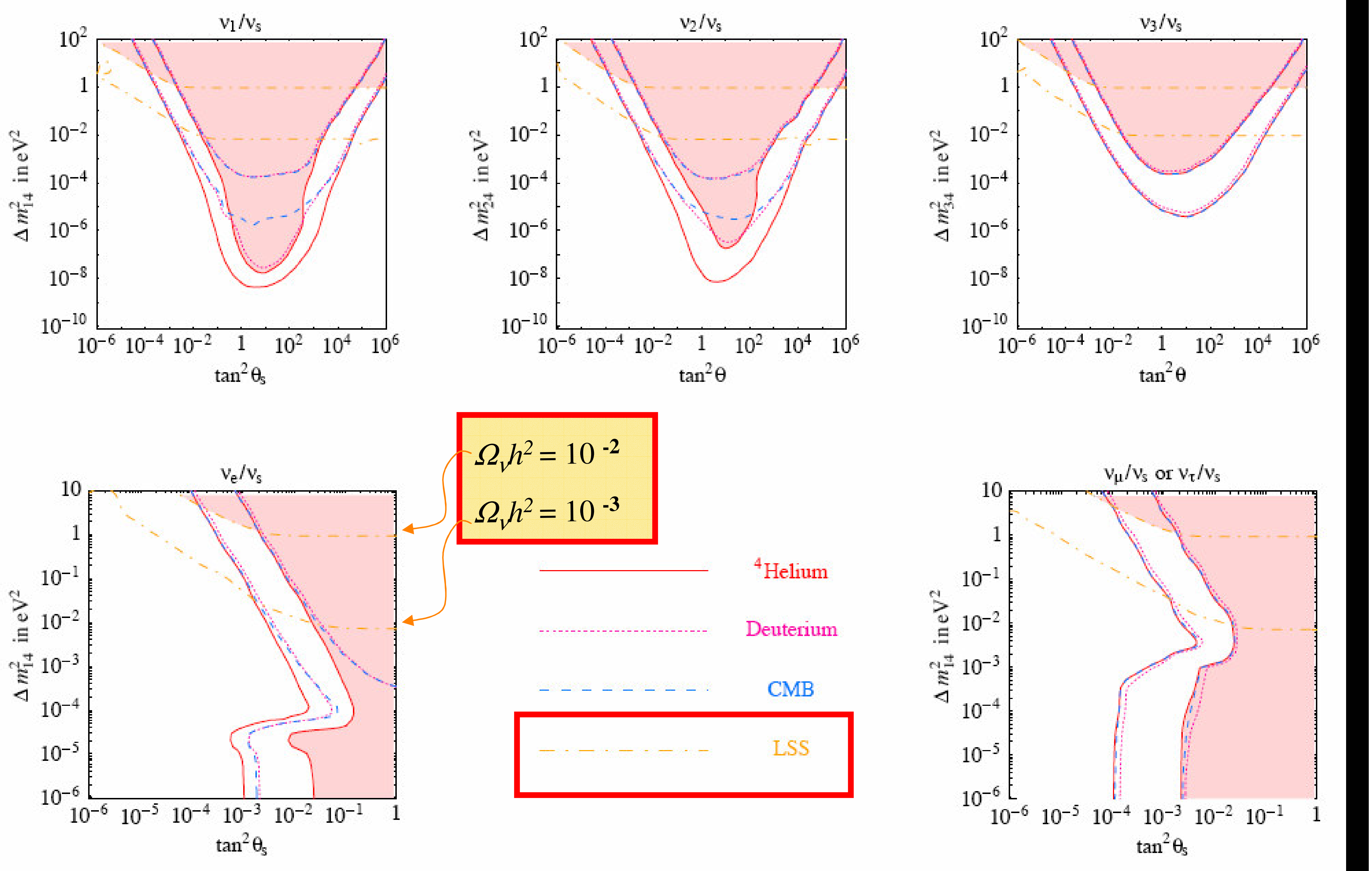
2dF+WMAP : $\Omega_\nu h^2 < 0.76\,10^{-2}$

⇩

ν_s contribute to $\Omega_\nu \Rightarrow$ **bound on m_s** i.e. **Δm^2_s** .
but: if ν_s do not fully thermalize $\Rightarrow \rho_{\nu s} << 1 \Rightarrow$ weaker bound

M.Tegmark webpage

Bounds in the parameter space



Cosmic Microwave Background

The primordial neutrino energy densities *affect* the acoustic peaks of CMB power spectrum.

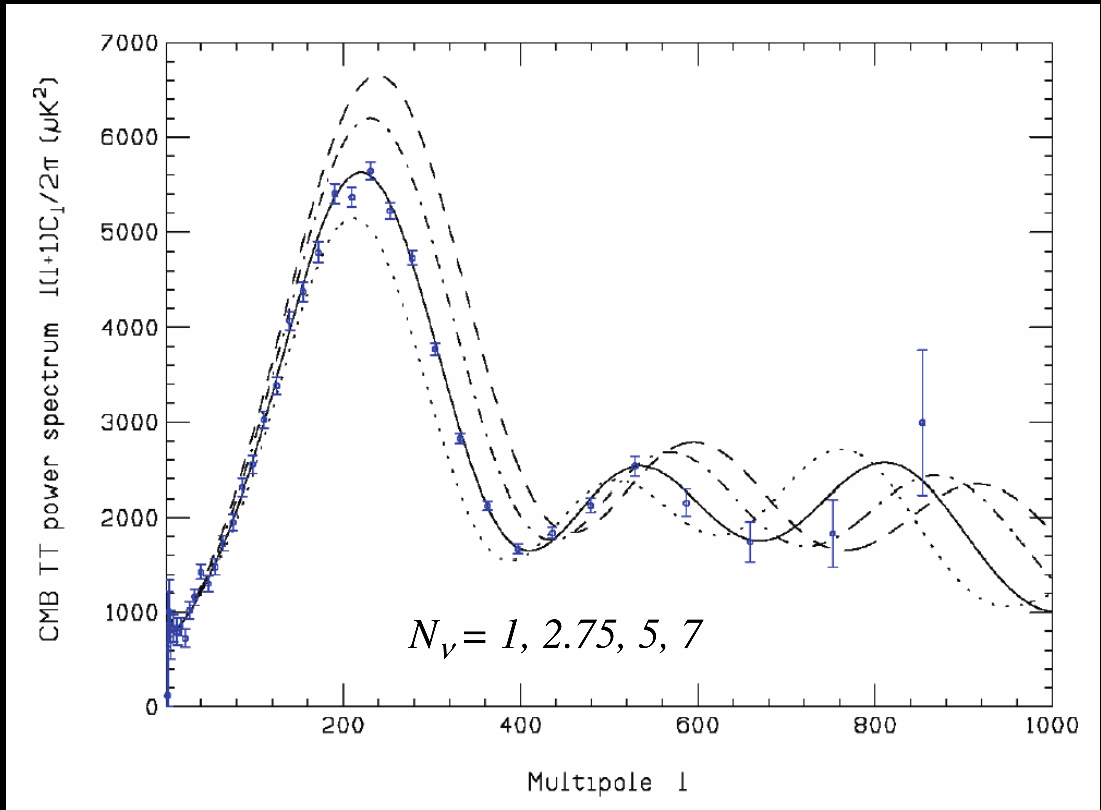
⇩

Bound on the effective $N_\nu^{CMB} \cong \rho_{\nu e}, \rho_{\nu\mu}, \rho_{\nu\tau}, \rho_{\nu s}$.

At present: $N_\nu^{CMB} = 3 \pm 2$

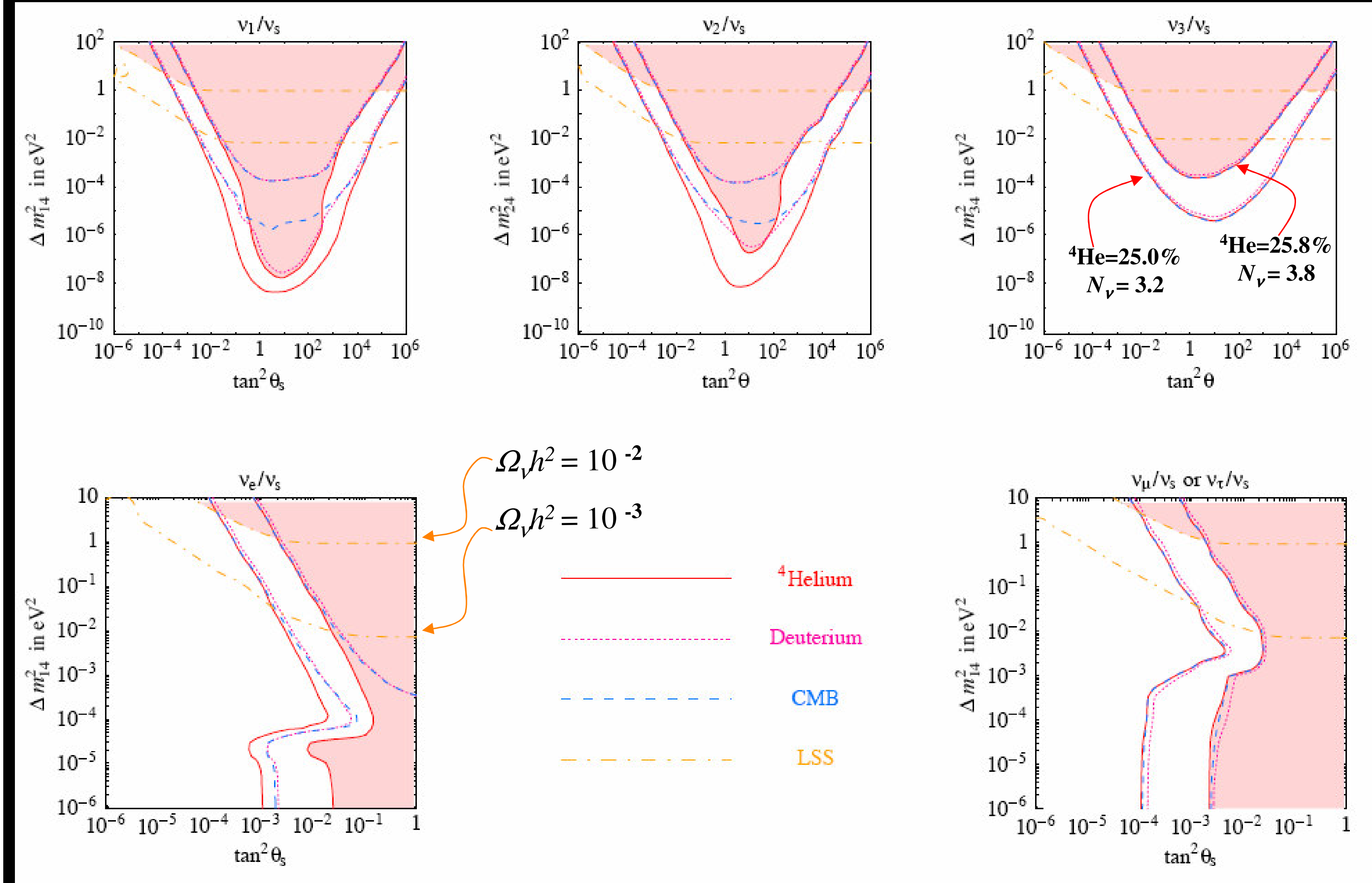
⇩

Bound on the $\boldsymbol{\Delta m_s^2}$, $\boldsymbol{\theta_s}$ (that determine the $\rho_{\nu s}$).



Barger et al., PLB566, 2003

All bounds from cosmology

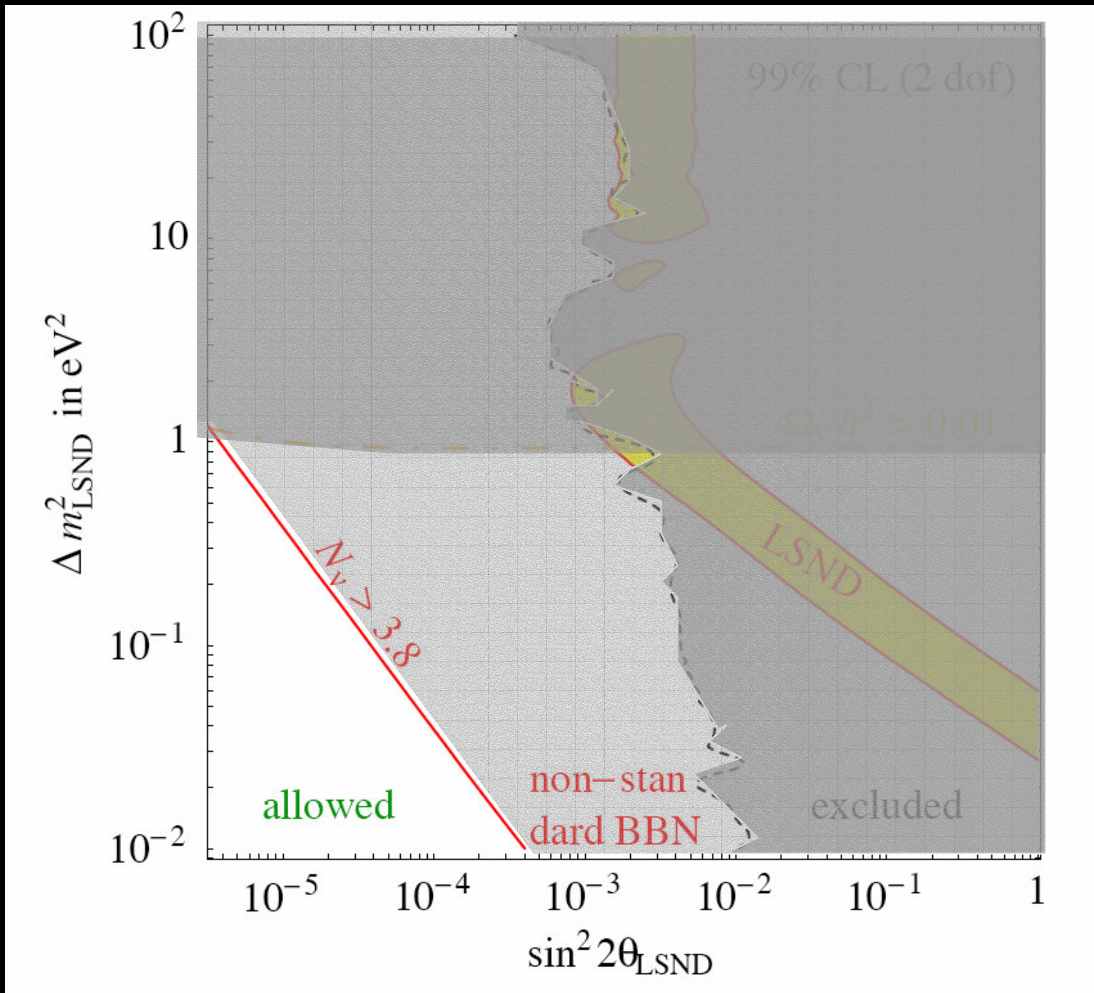


LSND: in or out?

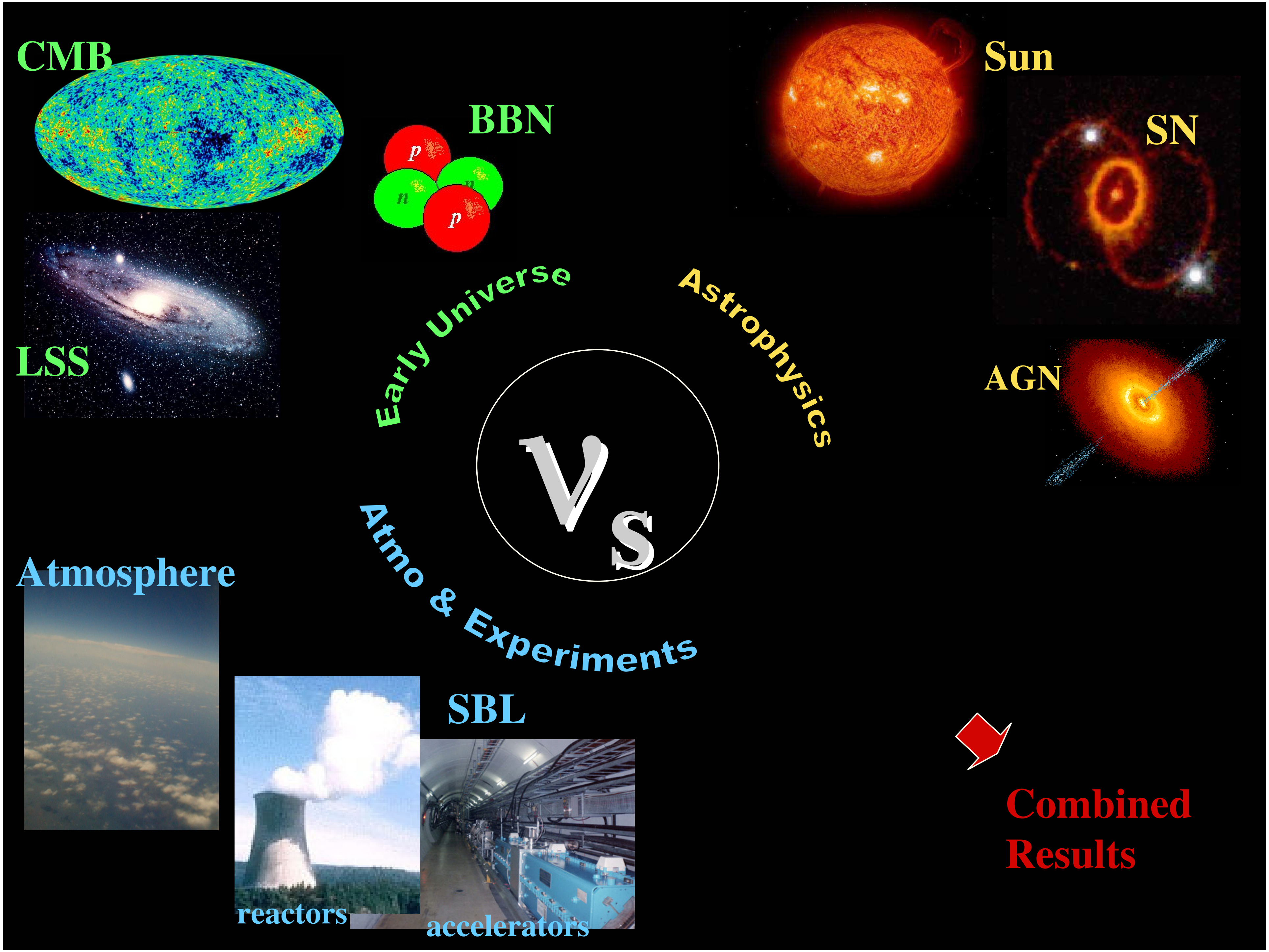
LSND claims evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ with $\Delta m^2 \neq \Delta m^2_{\text{sun, atm}}$ (if oscillations)

Requires a new (= sterile) neutrino: $\bar{\nu}_\mu \longrightarrow \bar{\nu}_s \longrightarrow \bar{\nu}_e$

How does the LSND ν_s fit in cosmology?



$\theta_{\text{LSND}} \sim \theta_{es}\, \theta_{\mu s}$


CMB
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Combined
Results

Sterile effects in SN

Neutrinos from SN:

(1) are a lot (99% of emitted energy)

(2) undergo "extreme" matter effects

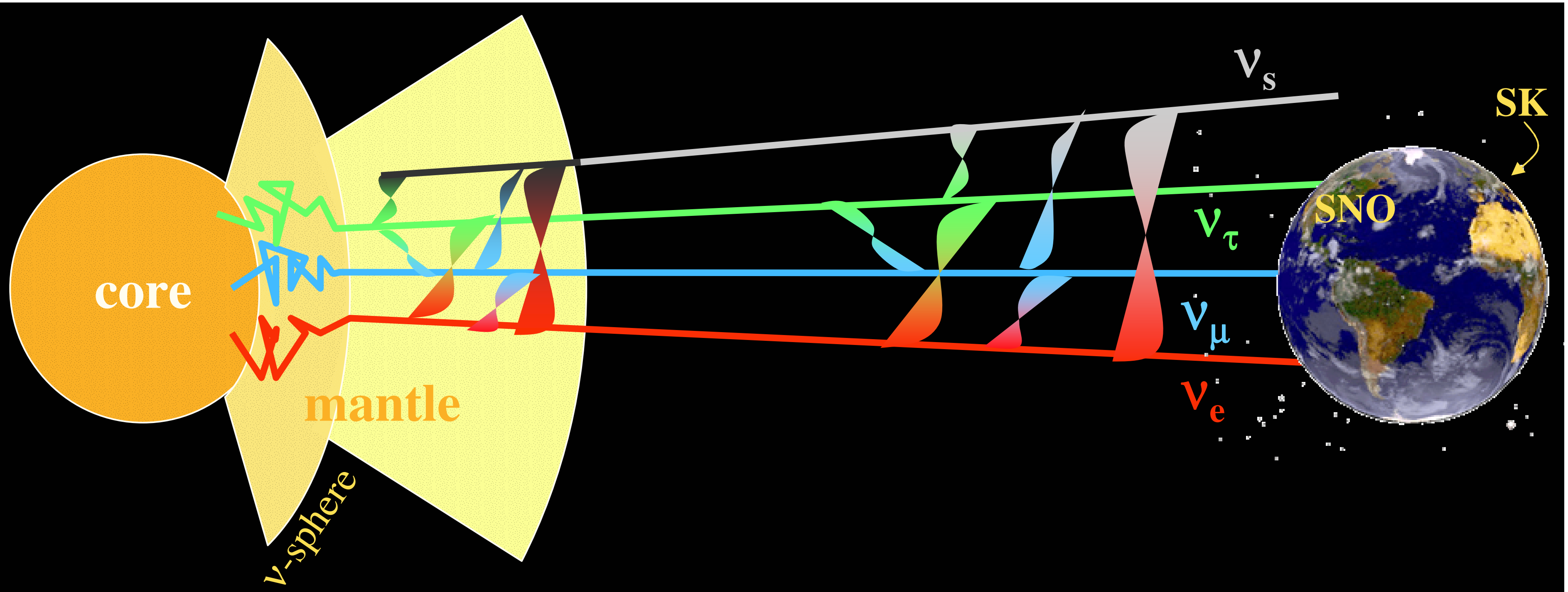
(3) come from very far away (~10 kpc)

(4) have the right energy (~*10 MeV*) for present detectors

An extra ν_s can make a big difference.

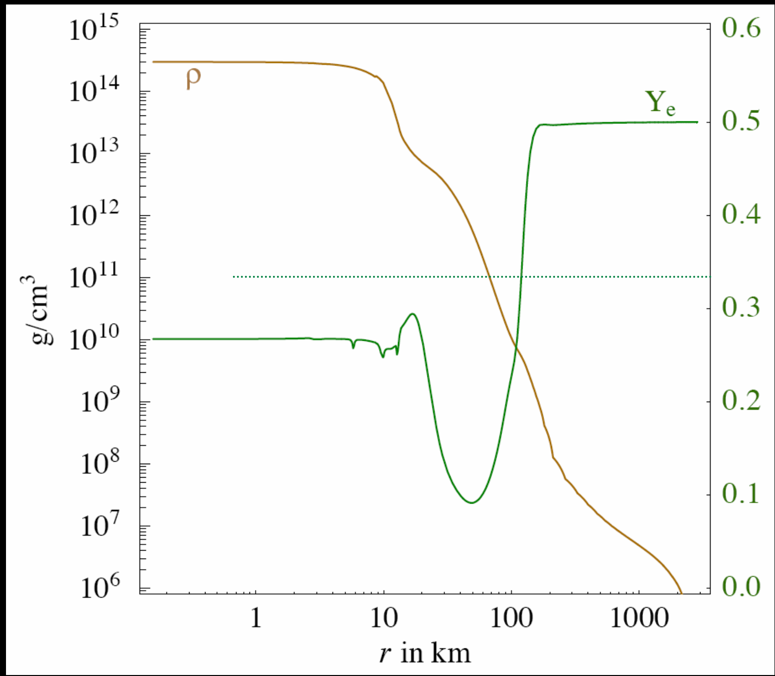
Overall picture confirmed by SN1987a ⇨ Set present bounds

Thousands of events from future SN ⇨ Propose future probes



Matter oscillations in the star mantle:

$$V_e = \sqrt{2} G_F n_B (3Y_e - 1)/2, \qquad V_\tau = V_\mu + V_{\mu\tau},$$
$$V_\mu = \sqrt{2} G_F n_B (Y_e - 1)/2, \qquad V_s = 0,$$



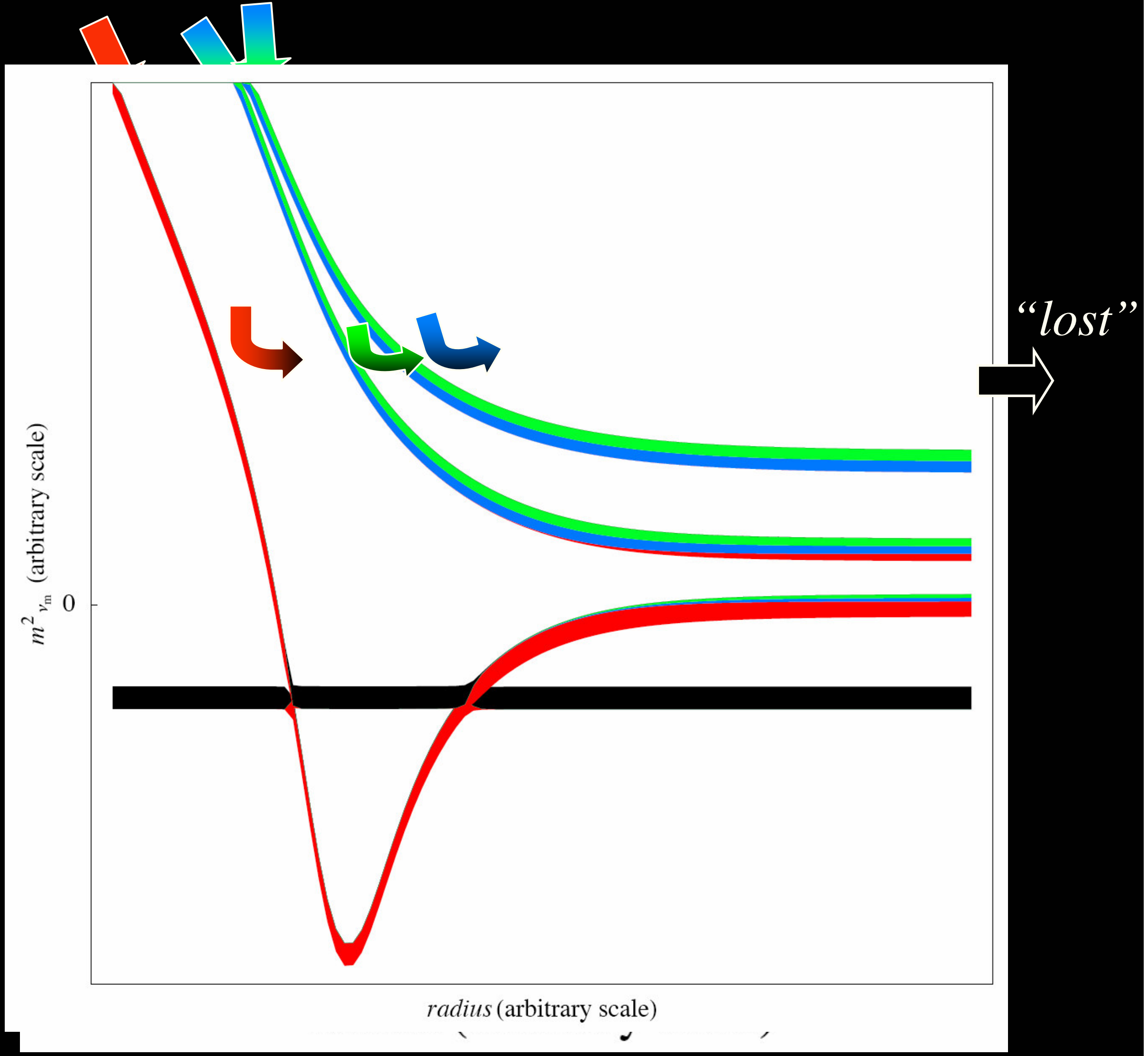
A.Burrows et al., 2001, 2002, 2003

Matter eigenstates
in the mantle:

At each crossing there is a crossing probability

$$P_C = \frac{e^{\tilde{\gamma}\cos^2\theta^m_{as}} - 1}{e^{\tilde{\gamma}} - 1}$$

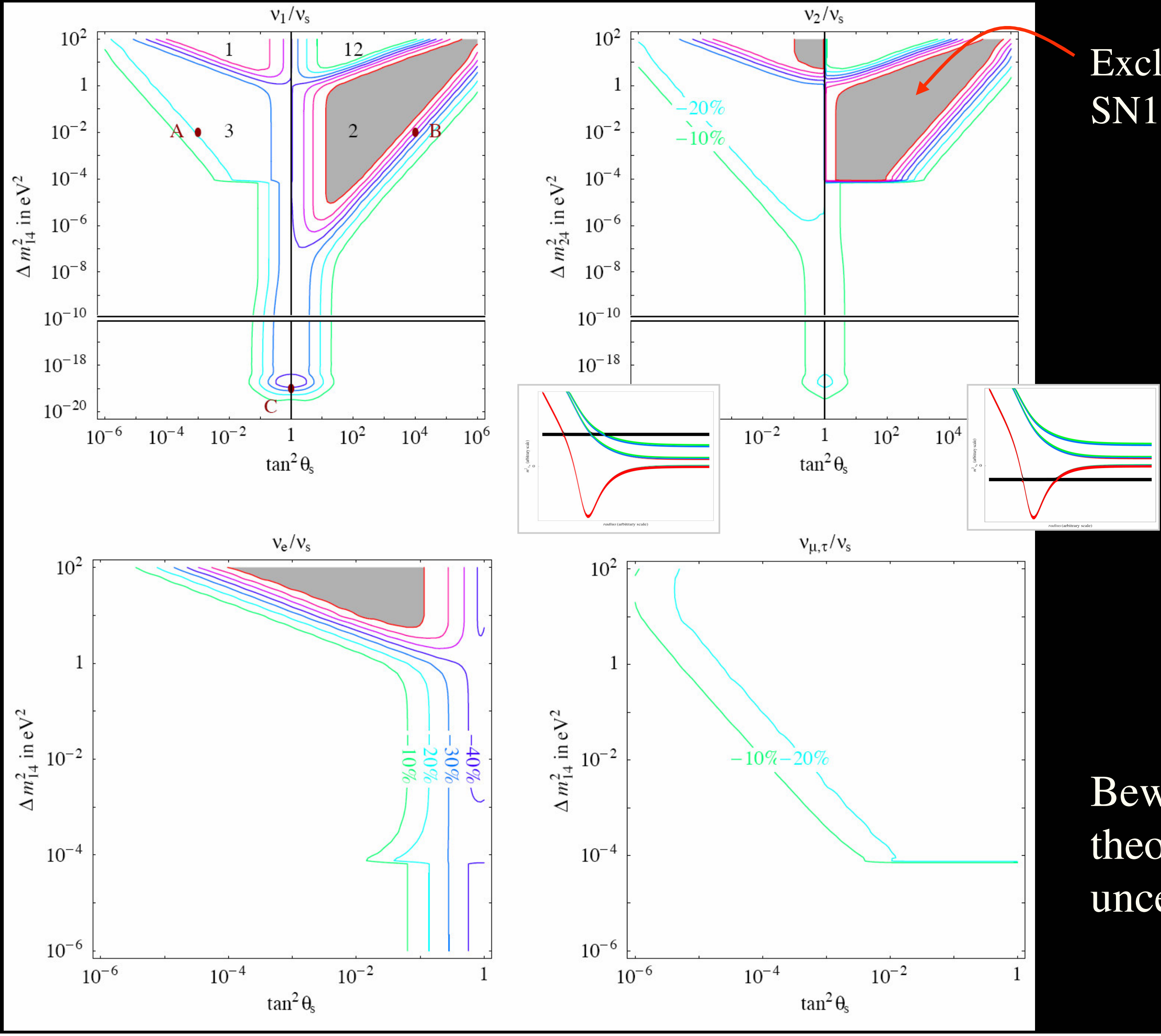
$$\gamma = \frac{4\mathscr{H}^2_{as}}{dH_a/dr} \equiv \tilde{\gamma} \cdot \frac{\sin^2 2\theta^m_{as}}{2\pi|\cos 2\theta^m_{as}|}$$



Output: final fluxes of ν_e, ν_μ and ν_τ on Earth .

Results: percentual reduction of $\bar{\nu}_e$ events (in a large Cerenkov detector)

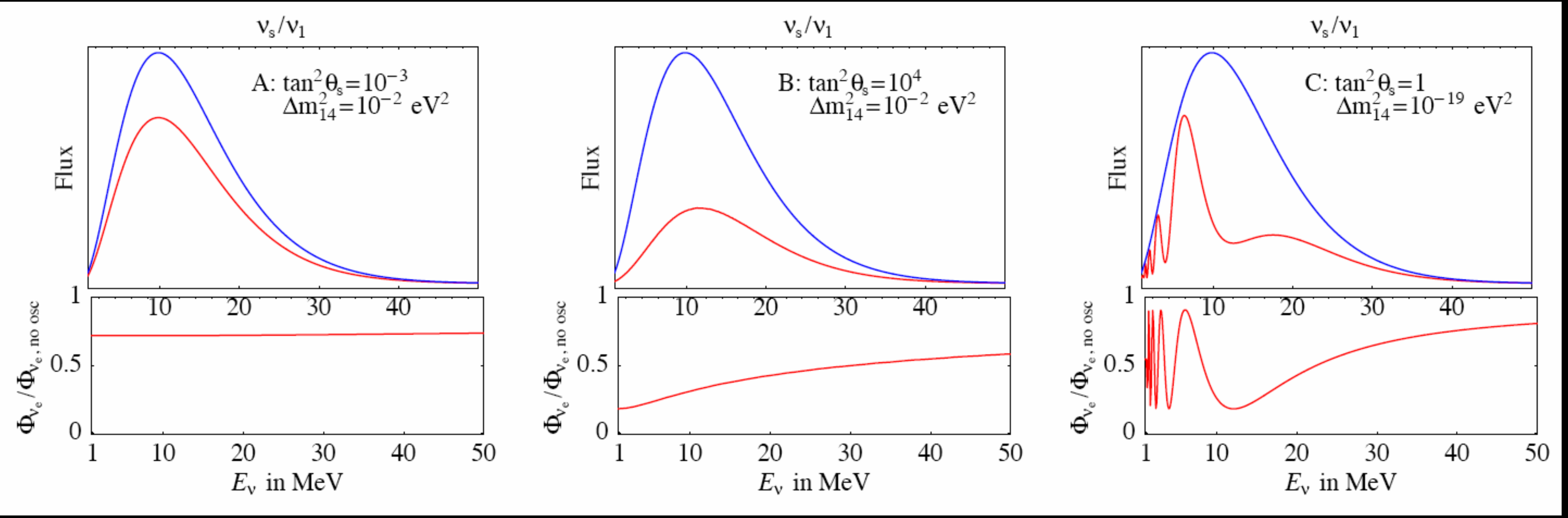
$(\bar{\nu}_e p \rightarrow n e^+)$



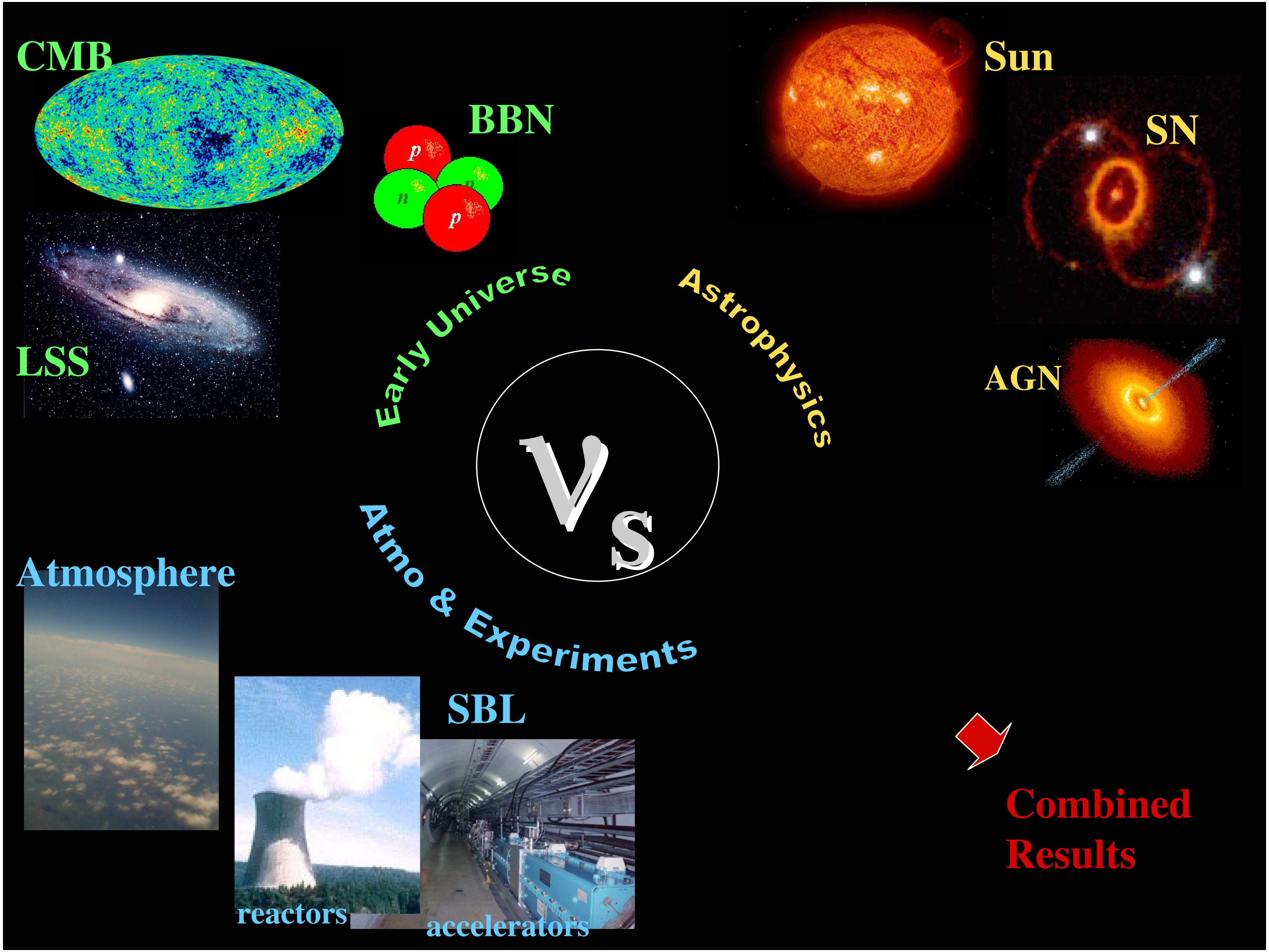
Excluded by SN1987a

Beware of theoretical uncertainties…

The energy dependance of matter/vacuum conversions causes **spectral distortions**:



Possible very clear feature!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SN
AGN
Astrophysics
ν_s
Atmosphere
Atmo & Experiments
SBL
reactors
accelerators
Combined
Results

Neutrinos from 'extragalactic' sources

- produced in high-energy astrophysical processes
- expected flavor ratios $e : \mu : \tau = 1 : 2 : 0$ at production

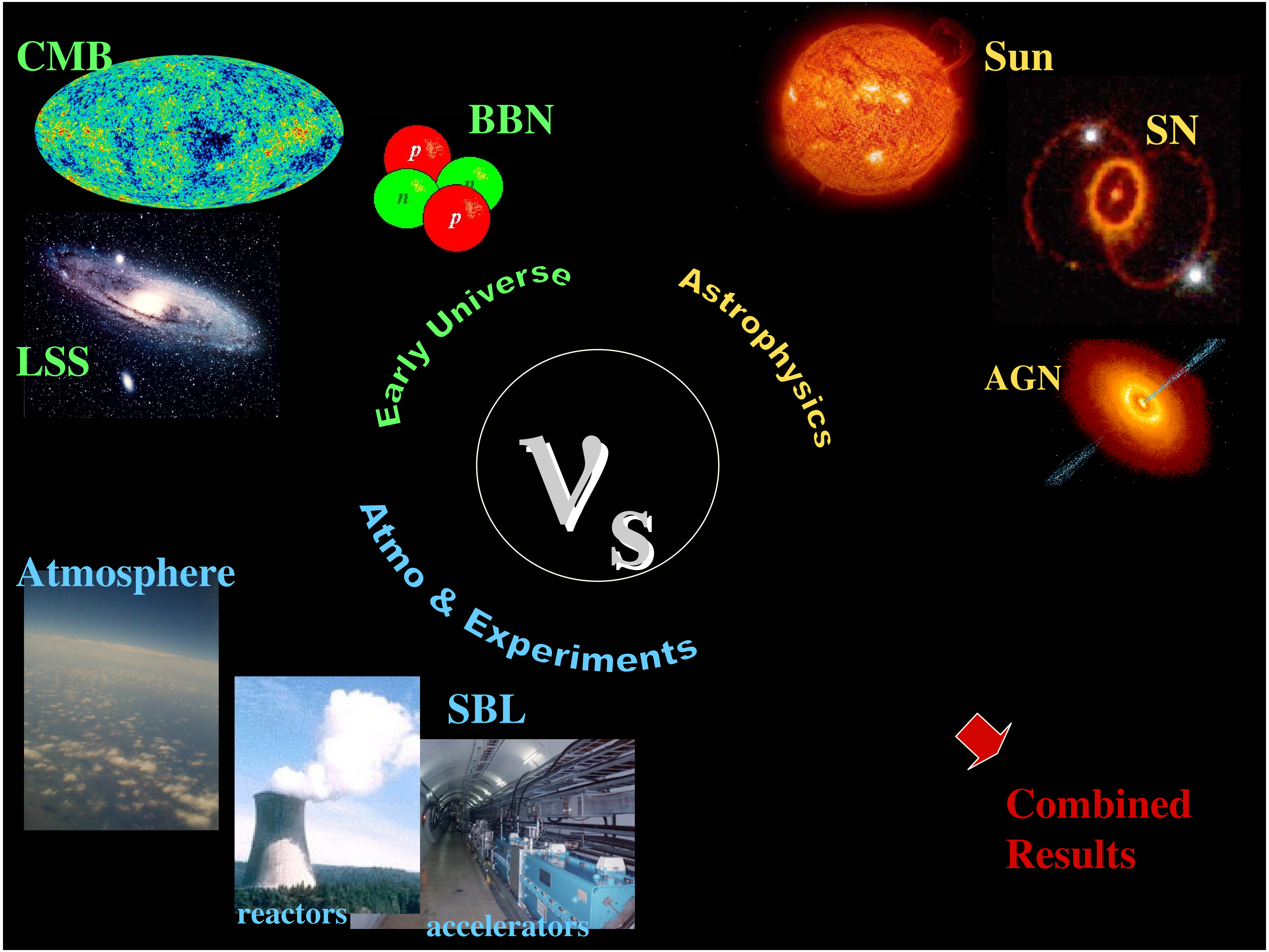
  $1 : 1 : 1$ after (active) oscillations
- if a ν_s is introduced, a selective depletion can occur .

But:

- initial fluxes totally unknown
- we tag ν_μ and ν_τ which nevertheless equiparate (atmo oscillations)…

⇩

Not a very interesting probe.



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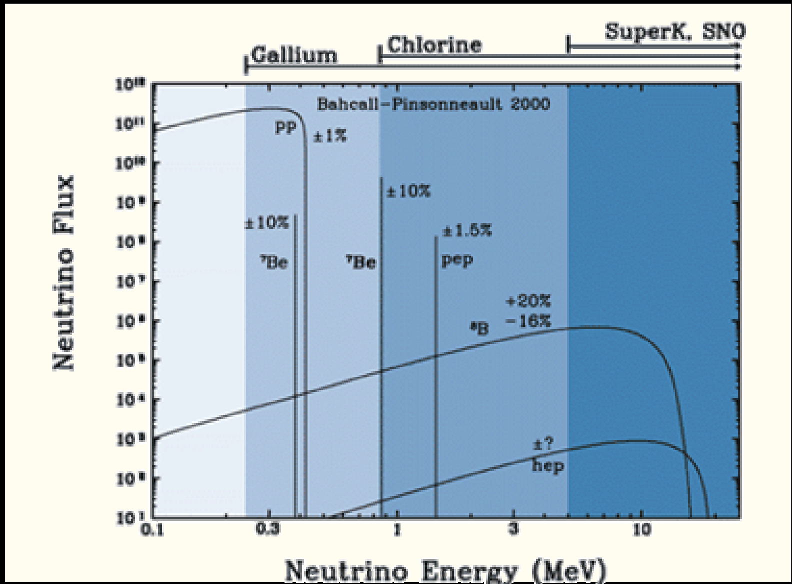
Sterile effects in solar neutrinos

Neutrinos from the sun:
(1) are a lot, and very well studied
(2) undergo matter effects in the sun and in the Earth
(3) come from far away (~150 Mkm)

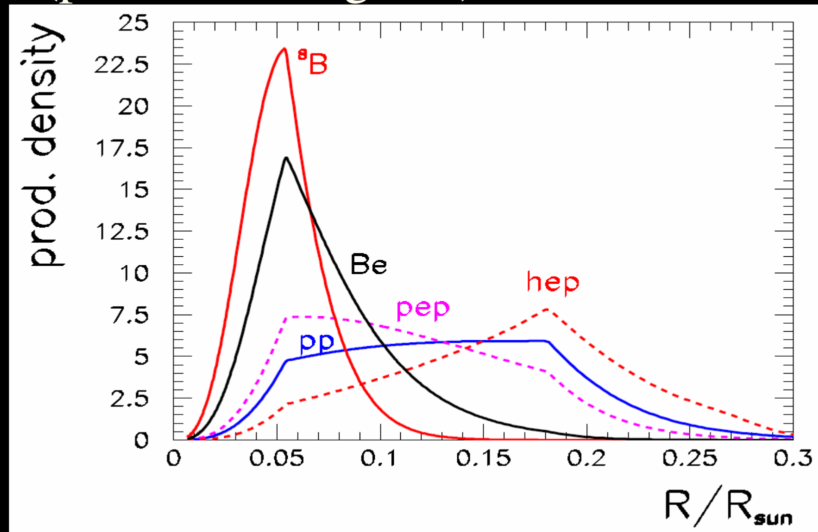
An extra ν_s can make a difference.

- Look for evidence of ν_s effects *around the LMA solution*. None
more details
- Set present bounds
- Identify future probes

Solar ν_e spectrum:

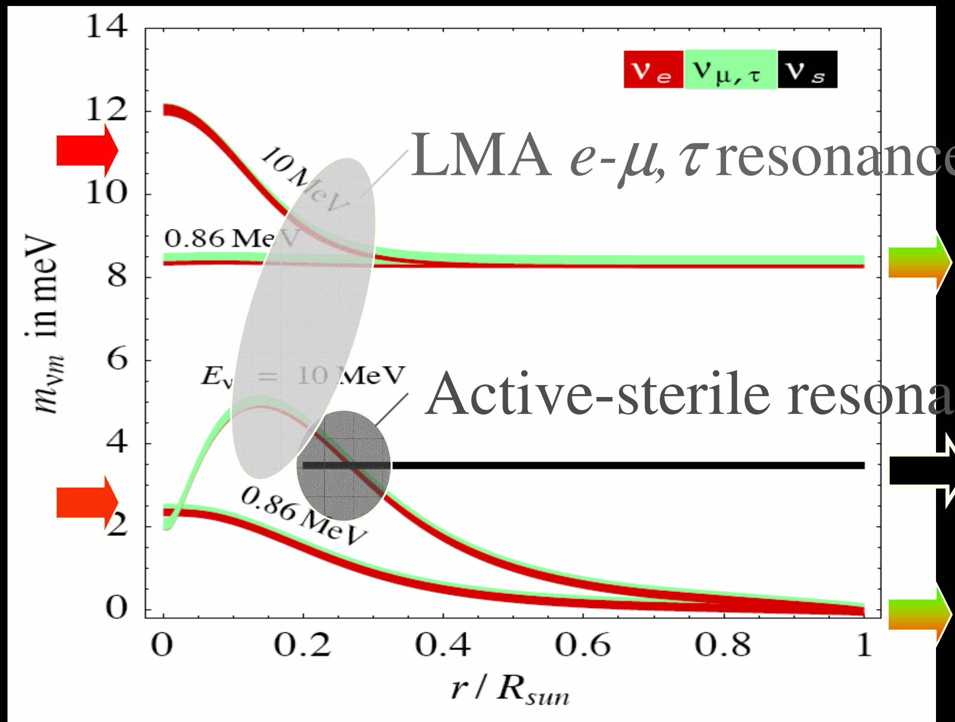


(production regions)



Evolution:

- -input ν_e flux
- -crossings in sun matter
- -output fluxes
- -vacuum oscillations
- -(matter oscillations in Earth)



Neutrino density matrix formalism:

4x4 density matrix ρ

at production (ν_e in the sun) is $\rho_m = V_m^\dagger \cdot \mathrm{diag}\,(1,0,0,0) \cdot V_m$

mixing matrices in matter (V_m) are computed diagonalizing the matter Hamiltonian

$$\mathscr{H} = \frac{mm^\dagger}{2E_\nu} + \sqrt{2}G_{\mathrm{F}}\mathrm{diag}\,(N_e - \frac{N_n}{2}, -\frac{N_n}{2}, -\frac{N_n}{2}, 0)$$

evolve ρ with evolution matrix $\mathscr{U} = \mathscr{U}_{\mathrm{earth}} \cdot \mathscr{U}_{\mathrm{vacuum}} \cdot \mathscr{U}_{\mathrm{sun}}$

at each ij matter level crossing $\mathscr{U}_{\mathrm{sun}}$ rotates of $\tan^2\alpha = P_C/(1-P_C)$

with $$P_C = \frac{e^{\tilde{\gamma}\cos^2\theta^m_{as}} - 1}{e^{\tilde{\gamma}} - 1} \qquad \gamma = \frac{4\mathscr{H}^2_{as}}{dH_a/dr} \equiv \tilde{\gamma} \cdot \frac{\sin^2 2\theta^m_{as}}{2\pi|\cos 2\theta^m_{as}|}$$

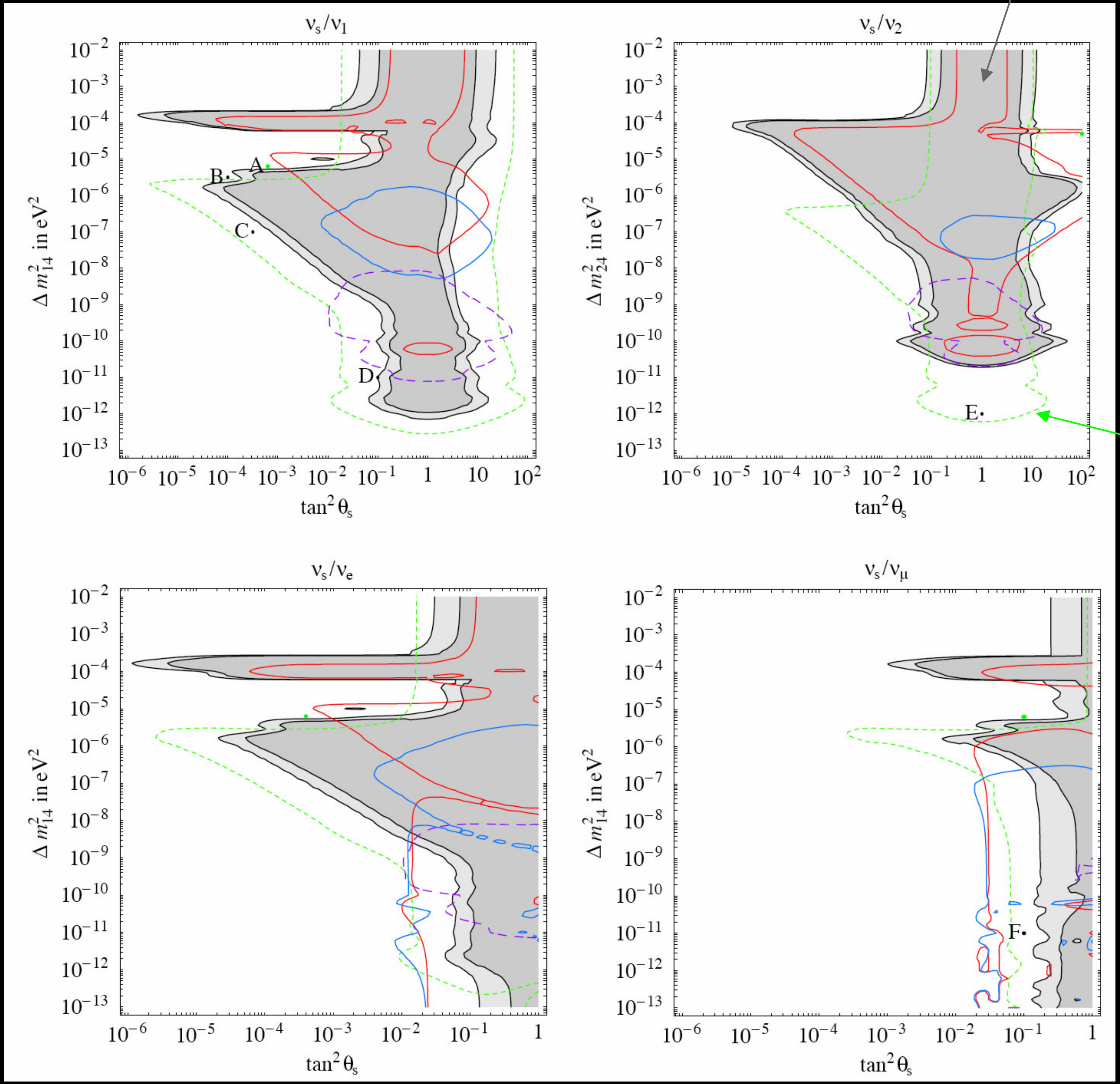
(θ^m effective mixing angle in matter)

at detection (back to flavor basis) $\rho = \langle V \cdot \mathscr{U} \cdot \rho_m(r, E_\nu) \cdot \mathscr{U}^\dagger \cdot V^\dagger \rangle$

E.g. $P(\nu_e \to \nu_e)$ corresponds to ρ_{ee}…

Results (with KamLAND):

excluded

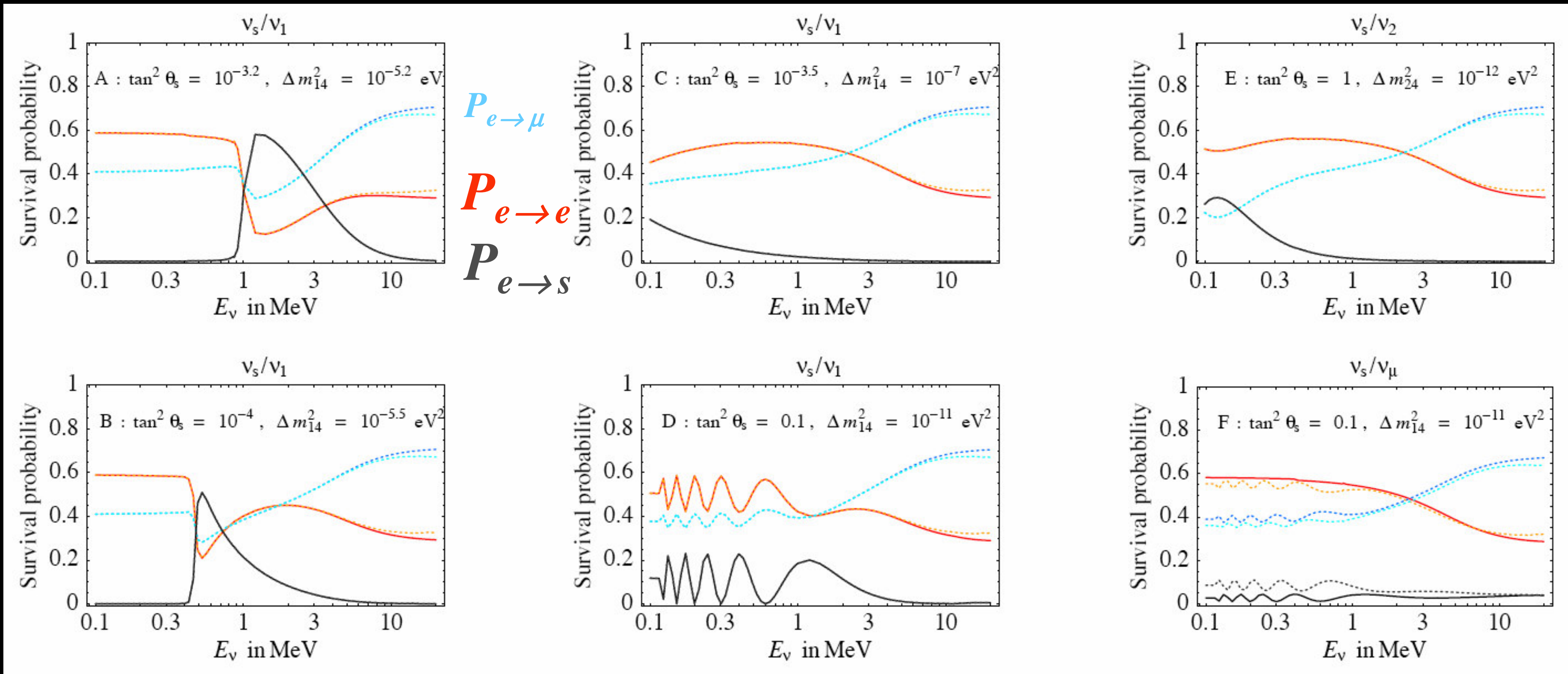


effect in a low energy exper. (sub-MeV)

Spectral distortions:

- the energy dependance in the (matter and vacuum) oscillations distorts the original (well known) solar ν_e spectrum

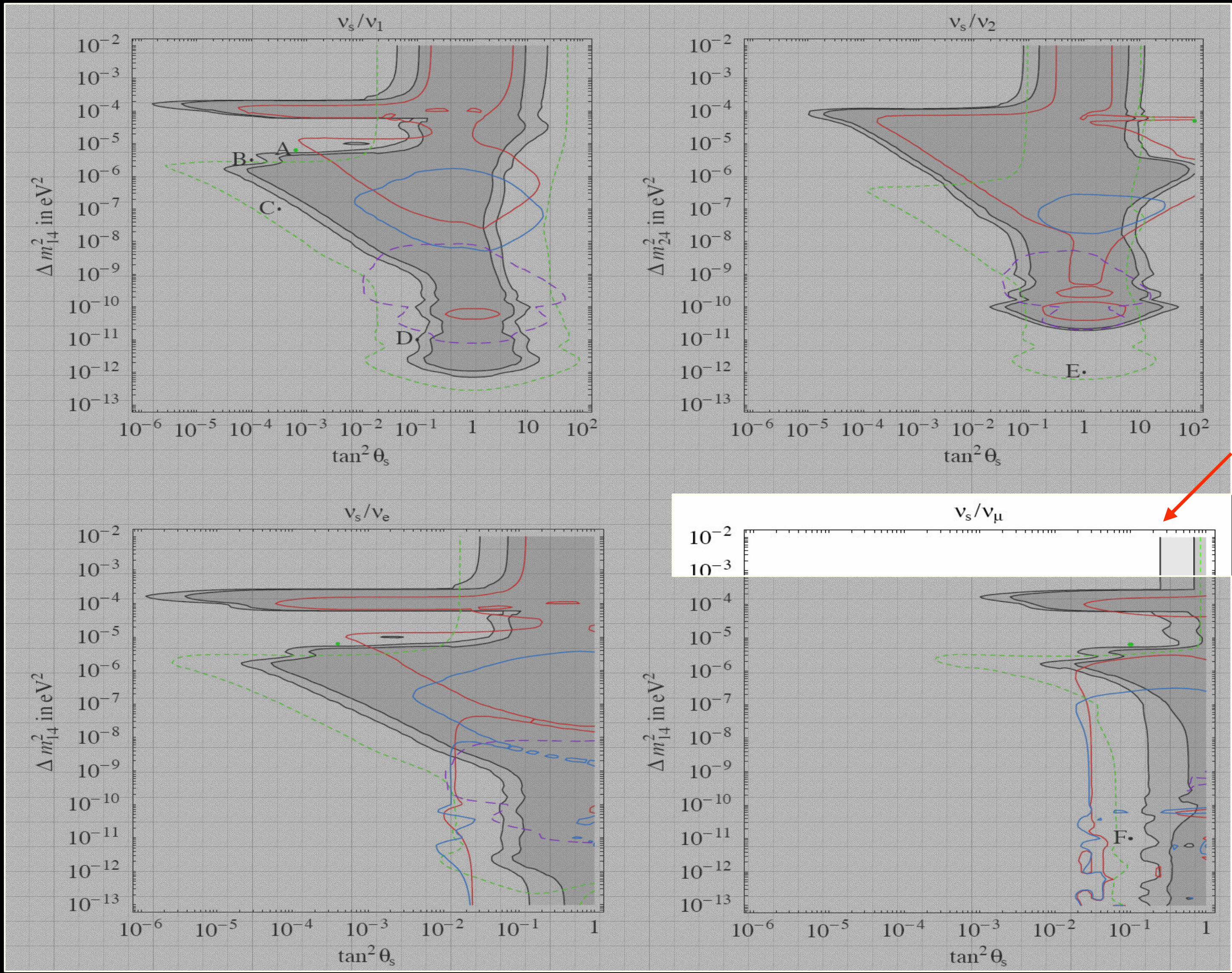
- a very distinctive feature!
- mainly at low energies



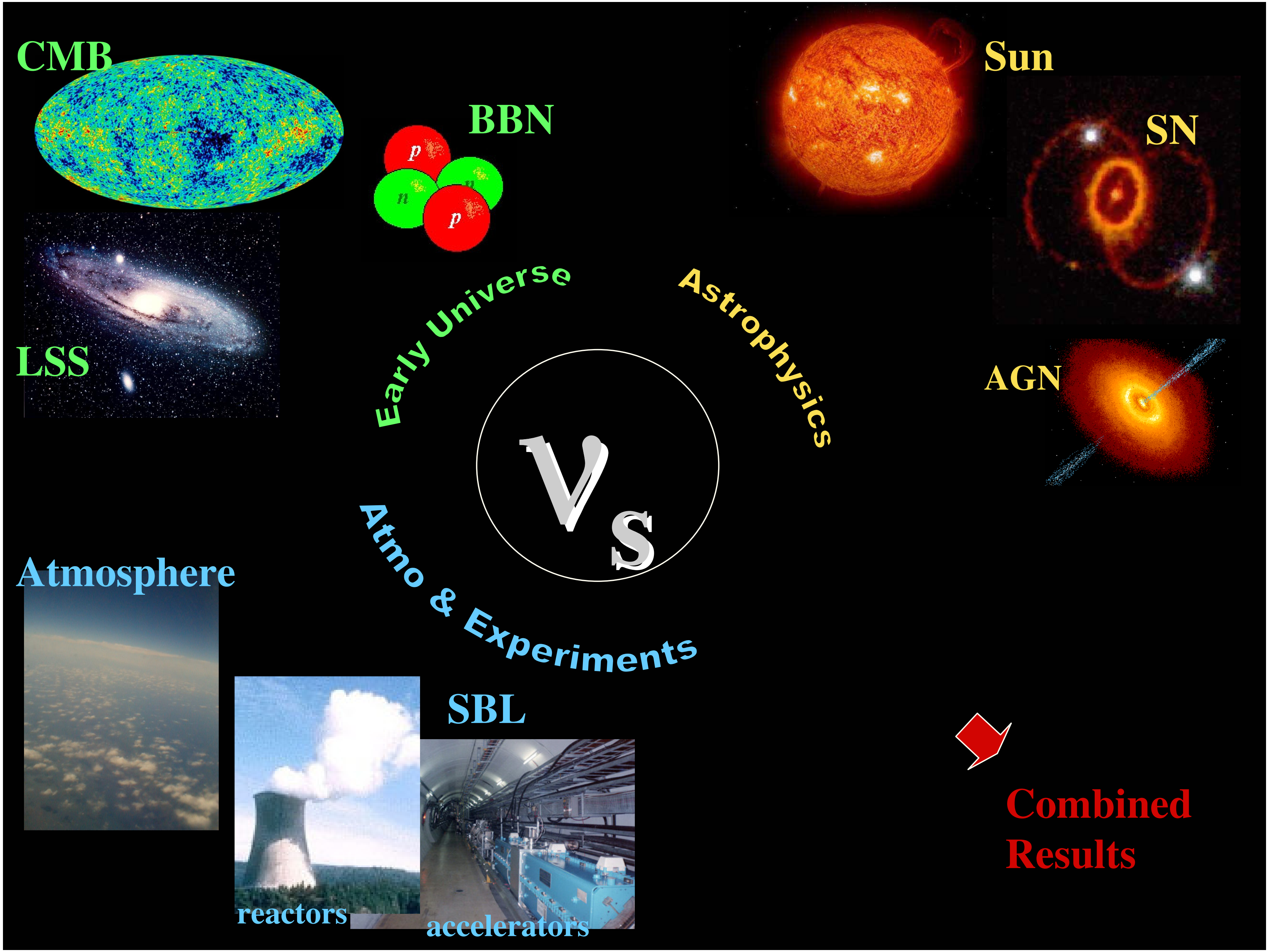
The "still allowed component" of ν_s in solar neutrinos:

means the naïve limit $\nu_e \to \cos\theta_s\, \nu_{\mu,\tau} + \sin\theta_s\, \nu_s$.

In our framework:



$\sin^2\theta_s < 0.2$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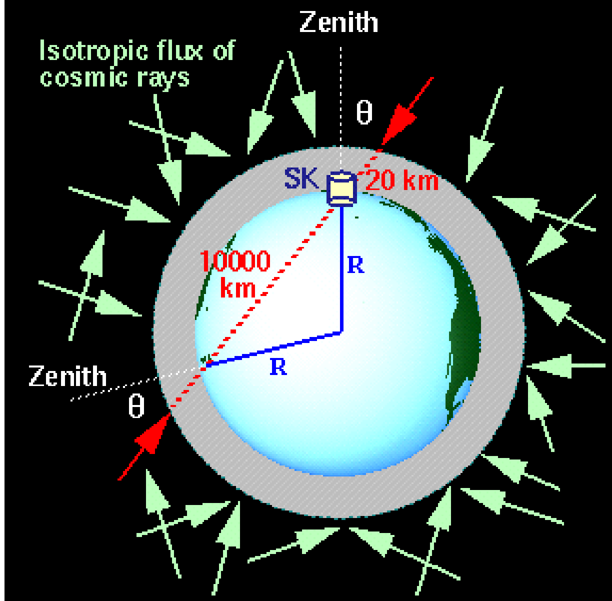
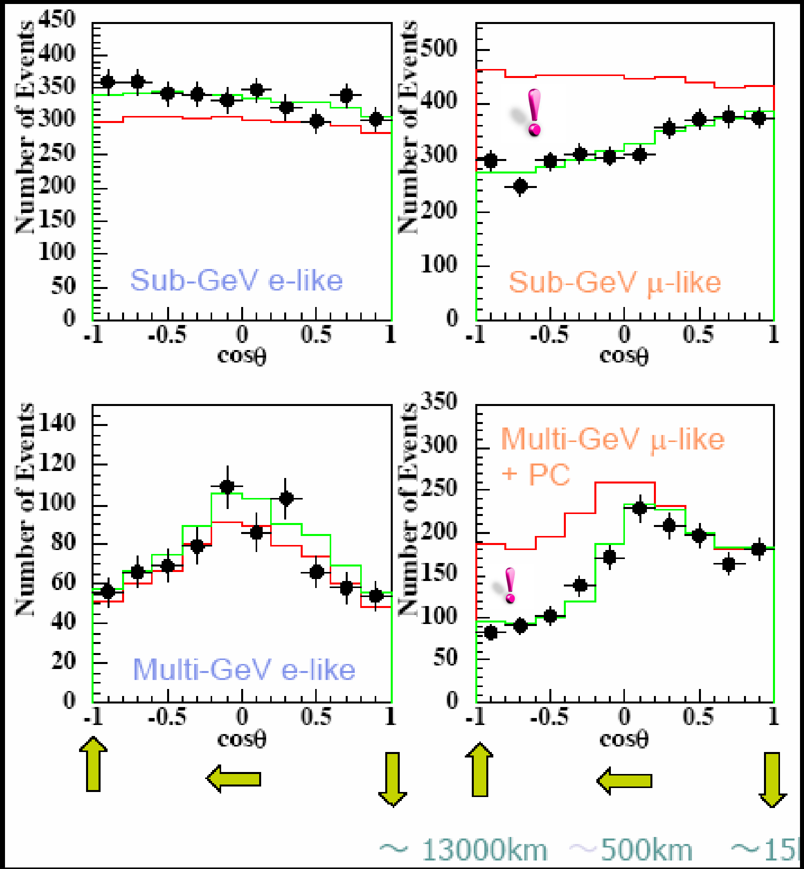
Sterile effects in atmospheric neutrinos

Basics:



Evidence for oscillations is disappearance of ν_μ "from below".



Where do they go? $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_s$ or a combination?

3 sensitive probes to discriminate and put bounds:

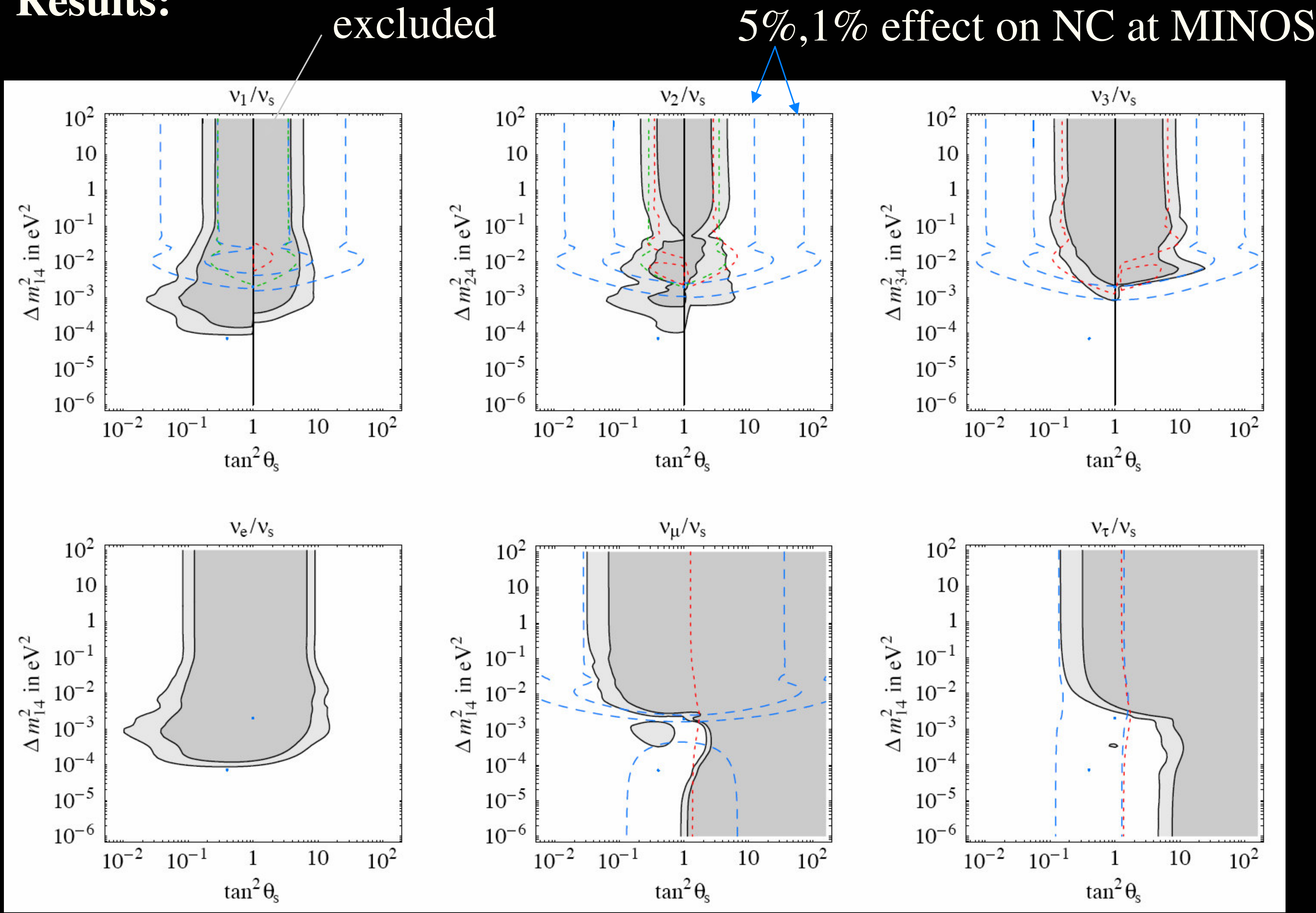
If $\nu_\mu \rightarrow \nu_s$:

(1) larger flux of thru-muons
(1b) larger number of PC events
(2) fewer NC-enriched events
(3) tau appearance…

We perform a global χ^2 analysis of
SK + Macro + K2K data.

"No improvements" w.r.t. pure $\nu_\mu \rightarrow \nu_\tau$ found:
$\Rightarrow$ no evidence for sterile neutrinos
$\Rightarrow$ excluded regions .

Results:

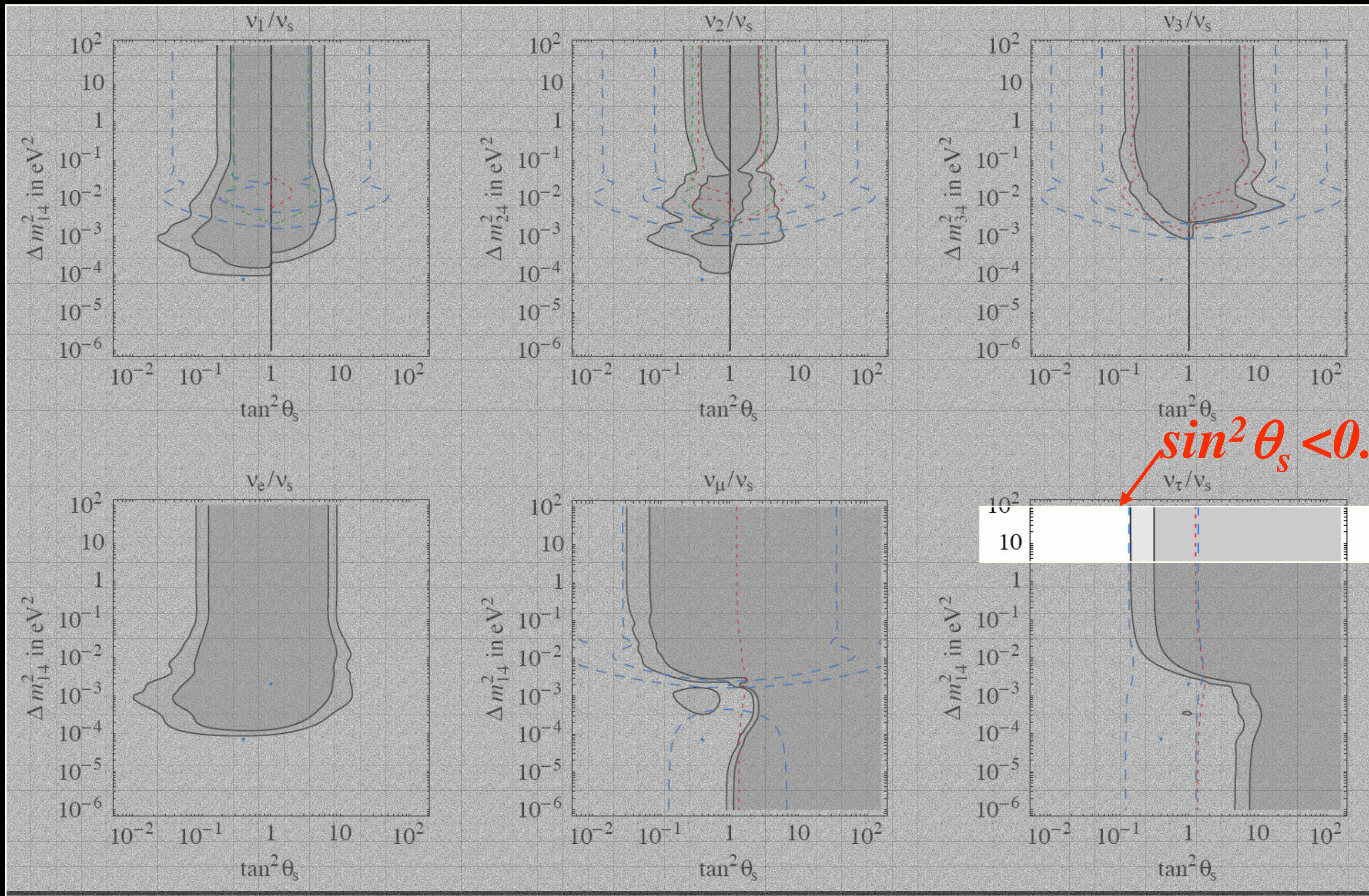


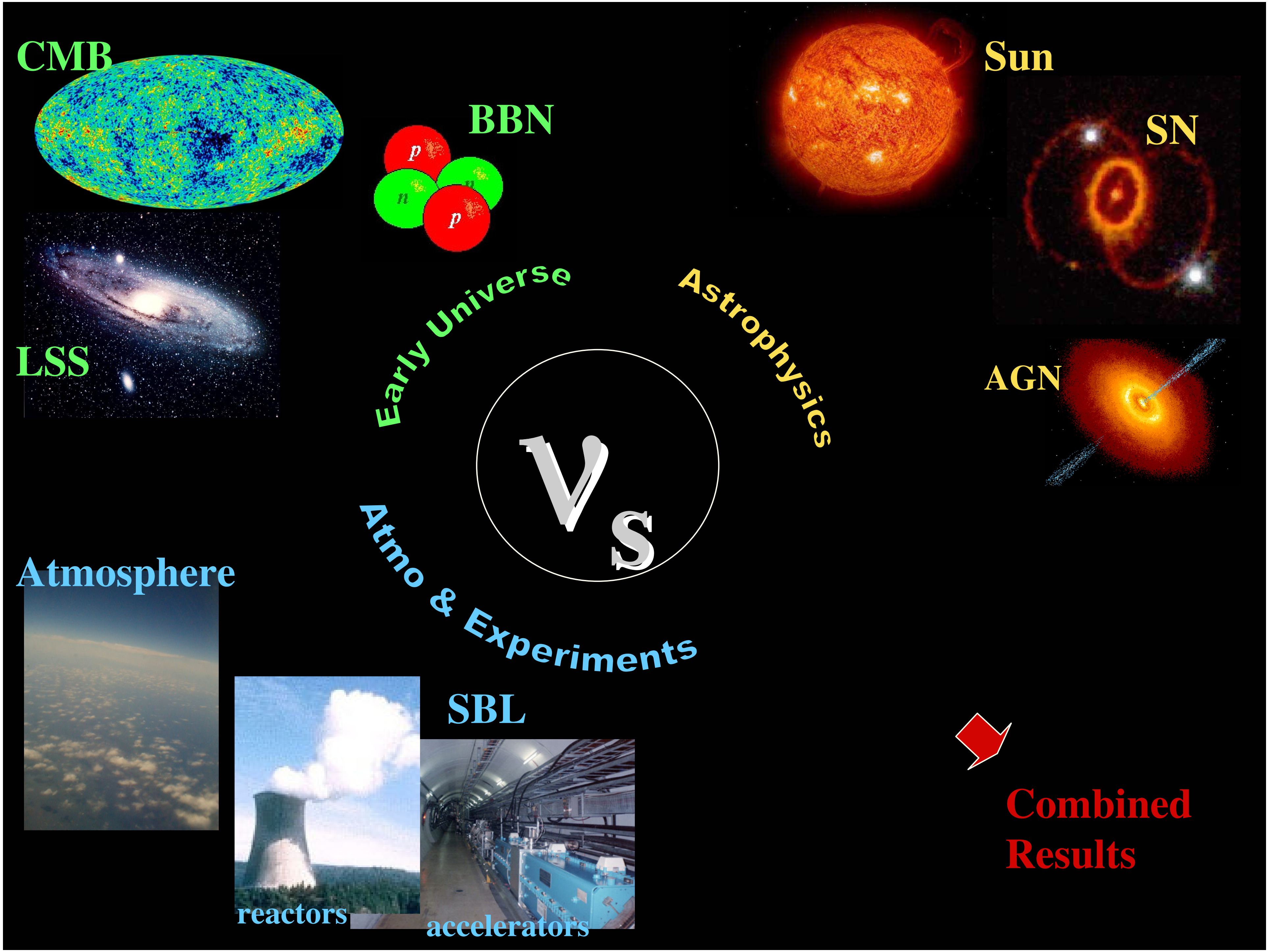
excluded
5%,1% effect on NC at MINOS
ν_1/ν_s
ν_2/ν_s
ν_3/ν_s
ν_e/ν_s
ν_μ/ν_s
ν_τ/ν_s
Δm^2_{14} in eV^2
Δm^2_{24} in eV^2
Δm^2_{34} in eV^2
$\tan^2\theta_s$
10^2 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6}
10^{-2} 10^{-1} 1 10 10^2

The "still allowed component" of ν_s in atmospheric neutrinos:

means the naïve limit $\nu_\mu \to \cos\theta_s\, \nu_\tau + \sin\theta_s\, \nu_s$.

In our framework:

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SBL
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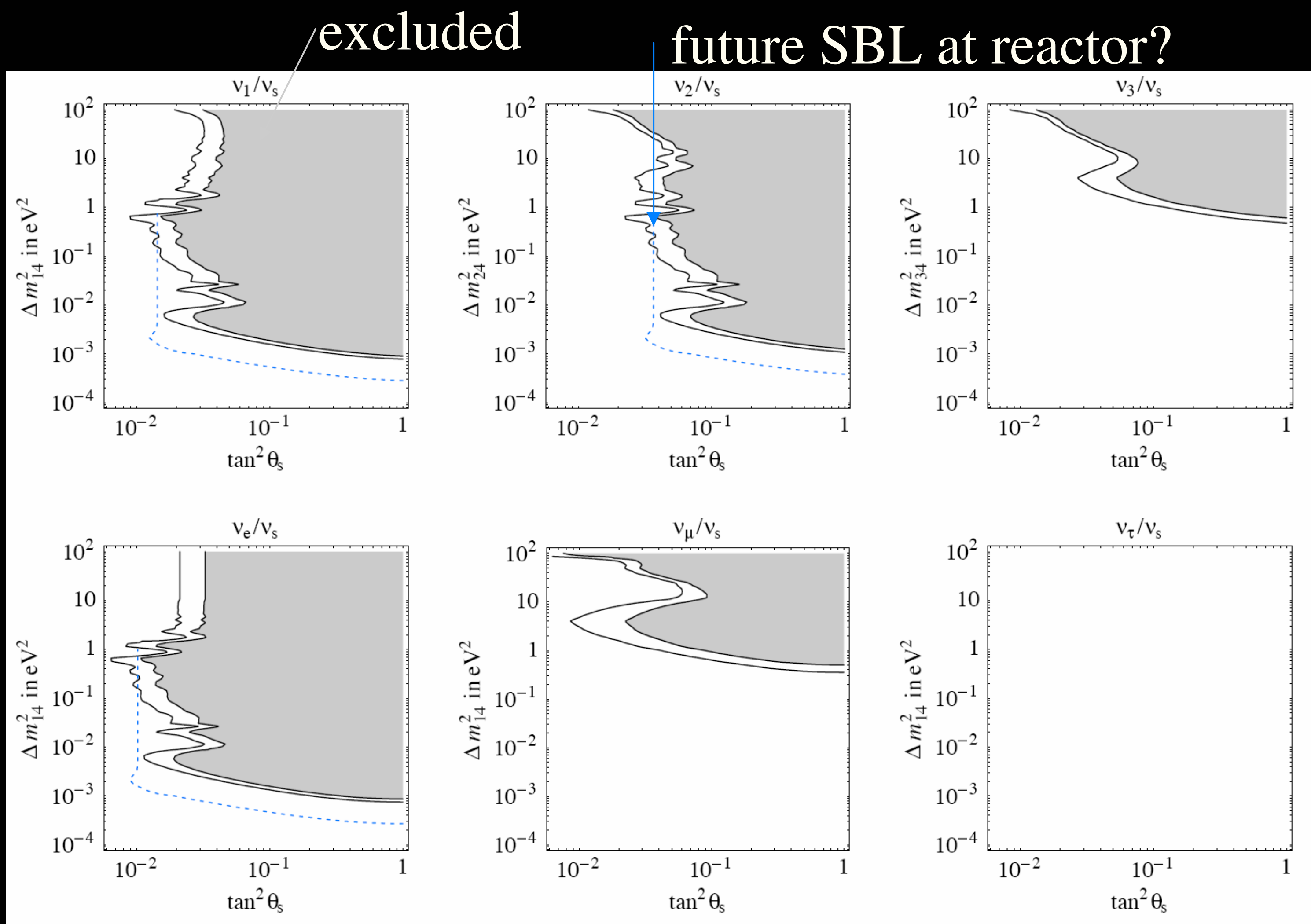
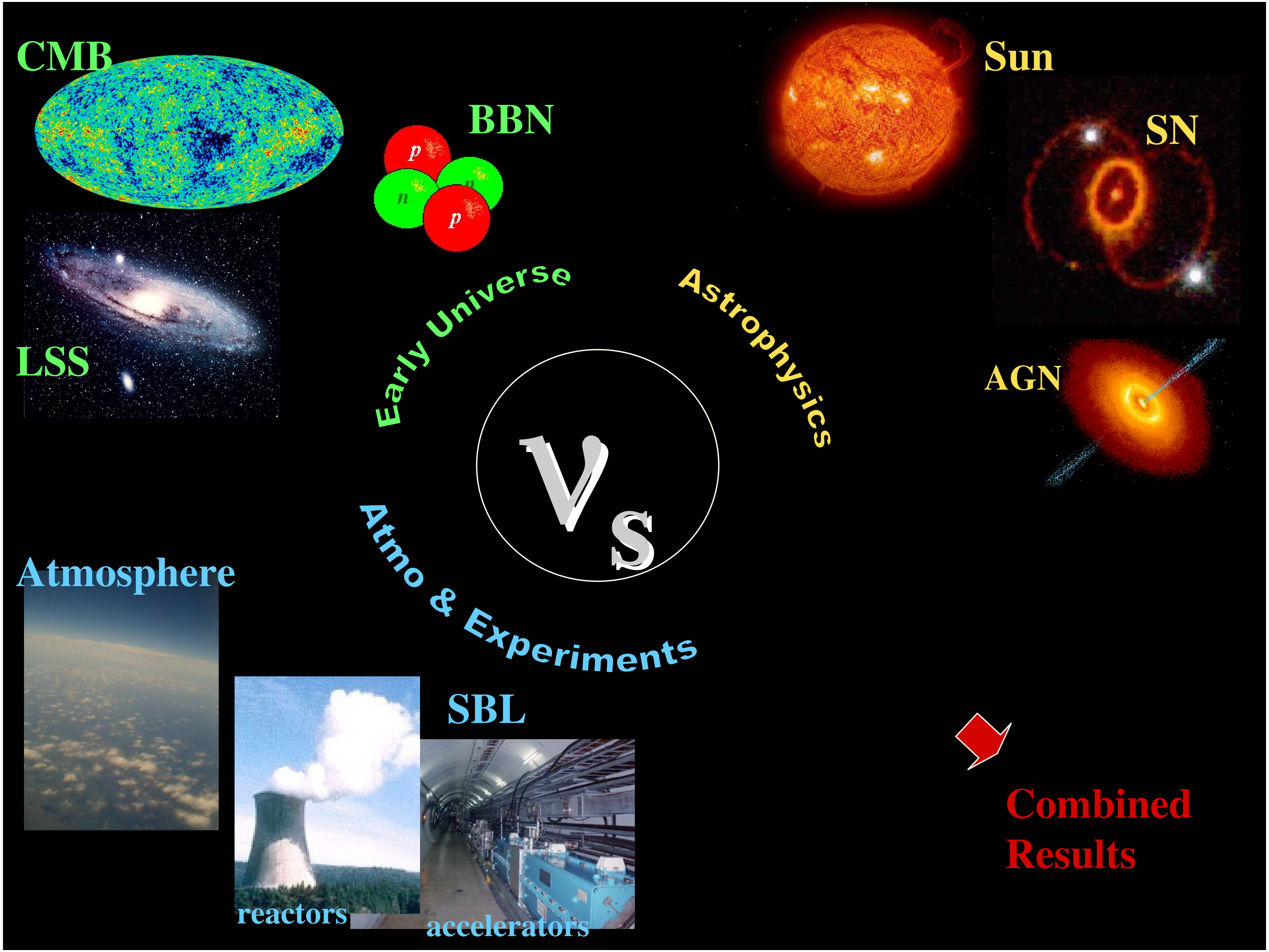
Sterile effects in SBL neutrinos

Chooz + Bugey + CDHS + CCFR + Karmen + Nomad + Chorus

Main constraint comes from “no-disappearance”.

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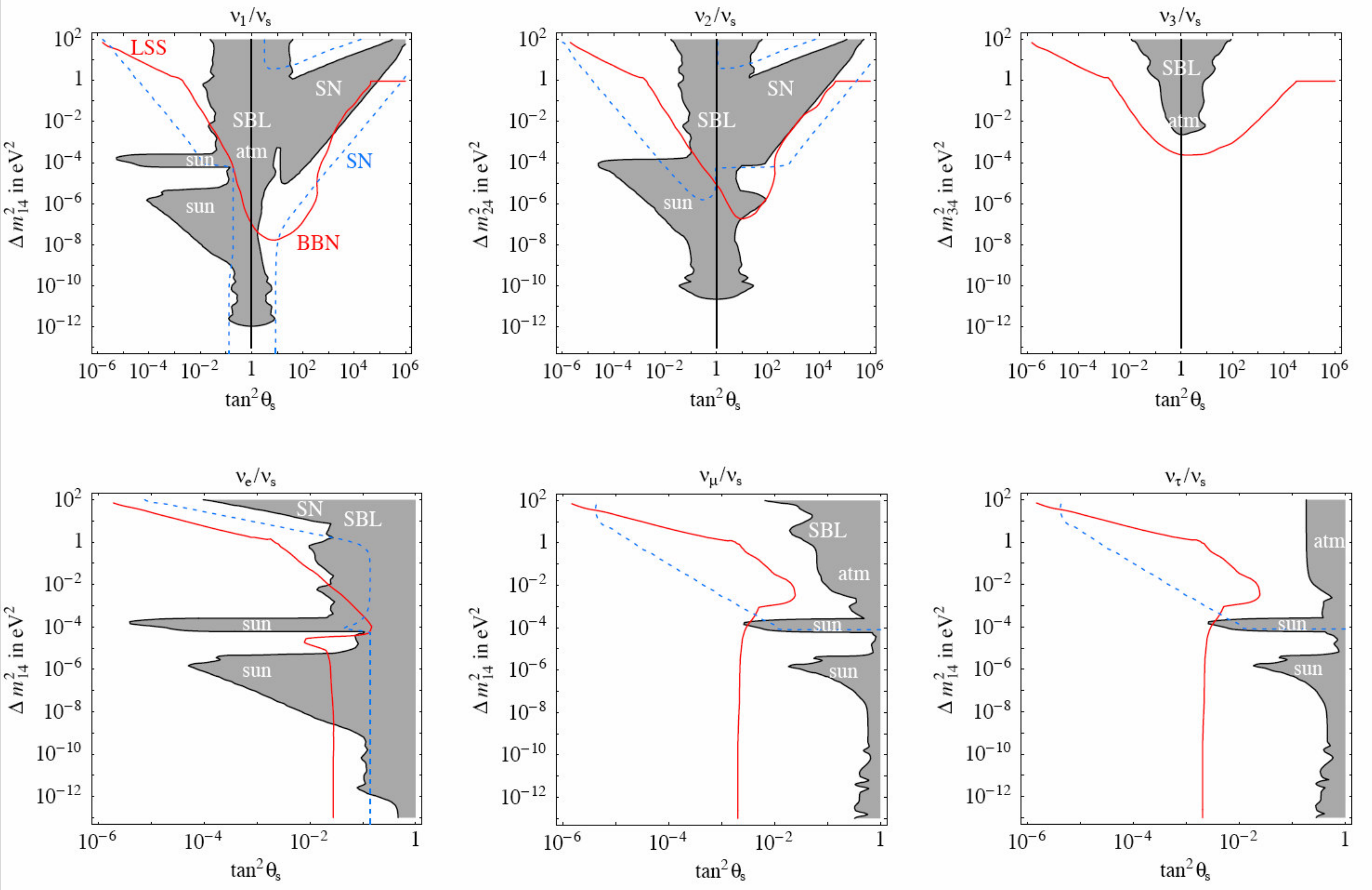

Conclusions

- the "direct/easy way" for sterile neutrinos to enter our world (solar anomaly, atmospheric anomaly) is now ruled out
- performing a **general analysis**, we looked at more subtle and more interesting manifestations
- we find **no evidence** for sterile neutrinos so far
- we set the **present bounds**
- we identify **several probes** (more precise BBN, CMB,
future SN explosions,
sub-MeV solar neutrinos, …)
- we show how LSND is really in trouble with cosmology (too)